Baseline and Multimodal UAV GCS Interface Design

Progress Report

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Abstract

To improve operational effectiveness for the Canadian Forces (CF), the Joint Unmanned Aerial Vehicle Surveillance Target Acquisition System (JUSTAS) project is acquiring a medium altitude, long-endurance (MALE) uninhabited aerial vehicle (UAV). In support of the JUSTAS project, Defence Research and Development Canada (DRDC) – Toronto carried out a literature review on relevant auditory and tactile displays in UAV simulation environments for the ground control station (GCS) interface in an effort to identify techniques to overcome human factors issues in the supervisory control of UAVs. This literature review was used to generate a number of different design proposals for multimodal displays (i.e., the presentation of information in the auditory, tactile, and visual modalities). Two of these displays, an engine RPM sonification and aggregate attitude upset tactile display, were chosen for further development and testing. These two interfaces were implemented in a GCS simulator. A proposal for testing the displays was provided as a starting point for further discussion.

Executive summary

Baseline and Multimodal UAV GCS Interface Design: Progress Report

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Background: An uninhabited aerial vehicle (UAV) is an aircraft system without an onboard pilot or crew. The UAV is controlled from a ground control station (GCS). Today's UAVs are highly automated and to some extent, autonomous. Some UAVs can perform automated take-off and landing (e.g., the CU-170 Heron used by the Canadian Forces). UAV developers argue that automation and autonomy provide several benefits: (a) increased flight safety; (b) simplified operations; (c) lower operating costs; and (d) reduced operator workload (Attar, 2005). However, these benefits are not always realized. Along with the benefits of automation, some disadvantages occur such as loss of situation awareness (Endsley and Kiris, 1995; Endsley, 1996), loss of supervisory control (Parasuraman, Molloy, Mouloua, & Hilburn, 1996; Sheridan, 1987), information deprivation that occurs from remote operations (Manning, Rash, LeDuc, Noback, & McKeon, 2004), and high workload levels for operators (Lee, 2008; Woods, 1996). These issues point to the need for improved interfaces to help operators remain in the loop and maintain situation awareness during the remote monitoring tasks typical of UAV monitoring.

Results: A literature review was completed on relevant auditory and tactile displays in UAV simulation environments. This literature was used to generate a number of different design proposals for multimodal displays. Two of these displays, an engine RPM sonification and aggregate attitude upset tactile display, were chosen for further development and testing. These two interfaces were implemented using the hardware provided by DRDC-Toronto. A proposal for testing the displays was provided as a starting point for further discussion.

Significance: The work described in this report is in support of the Canadian Forces (CF) Joint Unmanned Aerial Vehicle Surveillance Target Acquisition System (JUSTAS) project. The JUSTAS project entails the acquisition of a medium-altitude, long-endurance (MALE) UAV. This work investigates the efficacy of a multimodal GCS display for enhancing supervisory control for automated landing. It is expected that the findings from this study will have implications for the design requirements of a GCS interface for the JUSTAS project.

Future plans: Overall, these activities have allowed us to reach a state of readiness to move on to the next stage of the project. The next phase of the project involves refining the design of the engine RPM sonification and aggregate attitude upset displays, conducting the evaluation of the displays, and conducting the baseline GCS pilot study.

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1   Introduction

An uninhabited aerial vehicle (UAV) is an aircraft system without an onboard pilot or crew. The UAV is controlled from a ground control station (GCS). Today's UAVs are highly automated and to some extent, autonomous. UAVs can be directed to follow a pre-programmed mission; they can fly to designated waypoints, fly specific patterns, correct for course deviations and hold above a particular coordinate or target. Some UAVs can perform automated take-off and landing (e.g., the CU-170 Heron used by the Canadian Forces). UAV developers argue that automation and autonomy provide several benefits: (a) increased flight safety; (b) simplified operations; (c) lower operating costs; and (d) reduced operator workload (Attar, 2005). However, these benefits are not always realized. Along with the benefits of automation, some disadvantages occur such as loss of situation awareness (Endsley and Kiris, 1995; Endsley, 1996), operators being forced to perform supervisory control tasks (Parasuraman, Molloy, Mouloua, & Hilburn, 1996; Sheridan, 1987), information deprivation that occurs from remote operations (Manning, Rash, LeDuc, Noback, & McKeon, 2004), and high workload levels for operators (Lee, 2008; Woods, 1996). These issues point to the need for improved interfaces to help operators remain in the loop and maintain situation awareness during the remote monitoring tasks typical of UAV monitoring.

The work described in this report is in support of the Canadian Forces (CF) Joint Unmanned Aerial Vehicle Surveillance Target Acquisition System (JUSTAS) project. The JUSTAS project entails the acquisition of a medium-altitude, long-endurance (MALE) UAV. This work investigates the efficacy of a multimodal GCS display for enhancing supervisory control for automated landing. It is expected that the findings from this study will have implications for the design requirements of a GCS interface for the JUSTAS project.

This report is a mid-project progress report detailing the work that has occurred between September 2010 and March 2011 in order to prepare for a large scale study of two GCS designs. One of the GCS designs will be a visual interface (called the "baseline condition"), essentially simulating a typical UAV visually based GCS interface. The other design will be a multimodal interface where tactile and auditory information will be added to the interface to see if this new information can improve operator performance and situation awareness.

The objective of this report is to outline potential designs for the auditory and tactile information of the eventual multimodal interface. To meet this objective, the current auditory and tactile interfaces for UAV control are described in Section 2. Drawing from this literature, new auditory and tactile designs are proposed in Section 3.

2 Auditory and Tactile Displays for Enhancing Monitoring Automated UAVs

In the control of automated UAVs, GCS operators are responsible for monitoring the status of the UAV and ensuring that safe operation is possible. This task is important during the events leading up to the recovery of the UAV.. When abnormal events occur that may jeopardize the safe recovery of the UAV, operators are able to abort the landing. These decisions require information about the current status of the vehicle (e.g., the current altitude and attitude), the environmental conditions, and the current tactical situation. Therefore, it is important that UAV operators have access to and are able to process this information even under heavy workload situations in which they may also be responsible for other critical mission tasks such as examining sensory imagery and monitoring communications channels.

Multimodal interfaces are one possible solution to this challenging task of supporting the information needs of GCS operators. The visual channel is often overloaded by information in current UAV GCSs. The auditory and tactile sensory modalities are plausible alternatives for information presentation and attention cueing. In the following sections we will examine the current literature as it has discussed the use of auditory and tactile displays in UAV simulation environments. We will then provide a review of the auditory and tactile displays proposed for improving operator awareness during UAV autoland situations.

2.1 Literature on Auditory and Tactile Displays in UAV Simulation Environments

To date, there are few studies that have examined auditory and tactile displays in UAV simulation environments. Studies involving auto-landing systems and automated flight are even fewer still. In this section we discuss some of these studies and examine similarities and differences between them. We define UAV simulation environments as environments where the task is to control or monitor a single or multiple UAVs through a simulated mission. We have identified two types of simulations in the literature: those that involved manual control using a joystick or other analog methods, and those that relied on point-and-click interfaces and had a higher focus on supervisory control.

2.1.1 Manual Control UAV Simulations

In manual control situations, participants are often required to make small course changes in response to deviations from flight paths or to correct glide slopes. We identified three papers that made use of this type of simulation. Calhoun et al. (2003; 2004) used a UAV simulation environment consisting of a display with map and mission information, simulated video imagery from the UAV, and a third display for communications. Participants were asked to maintain the correct heading and airspeed of the UAV using a control stick and throttle control. The manual control of the UAV was largely dependent on the visual information presented by the interface; however, warnings were presented through visual, auditory, and tactile stimuli. In Calhoun et al. (2003), non-spatial alert cues were presented through the use of two tactors, one located on each of the participant's wrists. There were three levels of warnings that participants were required to respond to: non-critical warnings, critical warnings, and information queries. Figure 2.1 below

shows the different types of alerts used for each of these warnings in the baseline (visual and auditory) and tactile (tactile, visual, and auditory) alert conditions.

TASK	DIFFICULTY		ALERT CONDITION	
	LOW	HIGH	BASELINE	TACTILE
UAV Turns	1	3		
Normal Operations	2	4	No alerts for routine in-flight and waypoint update tasks	
Non-Critical Warnings	1	3	*Visual*: Colored "A" or "D" on HUD *Auditory*: Yes*	*Visual*: Colored "A" or "D" on HUD *Auditory*: Yes* *Tactile*: None; tactile reserved for Critical Warnings & Information Queries
Critical Warnings	3	3	*Visual*: Colored "A" or "D" on HUD *Auditory*: Yes*	*Visual*: Colored "A" or "D" on HUD *Auditory*: Yes* *Tactile*: One tactor vibrated: left-arm tactor: icing right-arm tactor: servo overheat
Information Queries	2	2	*Visual*: Red "QUERY" on HUD *Auditory*: None	*Visual*: None *Auditory*: None *Tactile*: Both tactors vibrated
*Auditory Alert: 0.4 second klaxon sound, primarily at 487 Hz; 10.3 dB.				

Figure 2.1: Alert conditions used in Calhoun et al. (2003, p. 2120).

Auditory information was presented in all alert conditions. The different levels of information were coded using the two tactors by varying the number of tactors vibrating and the location of the vibrating tactor. This limited the tactile signals to only three levels (left arm tactor for icing, right arm tactor for servo overheat, and both tactors for information queries). The tactors were mounted on the insides of the wrists and were placed 1.5 inches from the bottom of the participant's palms. The tactors were driven using a 5 volt square wave with a 50% duty cycle that had a frequency that changed from 250 to 500 Hz over a 0.1 second interval.

Calhoun et al. (2003) found that the tactile condition produced significantly faster responses than the baseline condition for information queries, but not for any of the other tactile alerts. Calhoun et al. (2003) suggested that this may have been because two tactors were used for the information query alert, while only one tactor was used for the warnings. However, the two warning conditions were also accompanied by an auditory alert while the information query condition used only a tactile alert (in addition to the visual alerts provided in all conditions). The authors caution that this study could not provide further insight into whether the significantly faster responses were created by having two vibrating tactors instead of just a single vibrating tactor or the absence of the redundant auditory cue. The information query tactile alert was entirely tactile while the baseline condition was entirely auditory. The warning alerts featured multi-sensory alerts that used vision, audition, and touch in the tactile condition. While it was possible that the use of tactile alerts could prove to be distracting, especially when two (auditory and visual) sensory modalities were already employed, the results suggested that tactile cues, in the presence of auditory and visual cues did not hinder or improve performance. However, uni-modal tactile cues (the tactile information queries condition) did produce faster response times than uni-modal visual cues (the baseline information queries condition). The participants' performance during the tracking/flight task was also analyzed, however no significant effects of alert types were found. This led the authors to conclude that the introduction of the tactile cue did not allow the participants to direct more resources to the flight task.

In a subsequent study, Calhoun et al. (2004) used a similar UAV simulation task but changed the type of auditory and tactile alerts used. The tactors were again placed on the inside of both wrists. However, instead of using three different alerts (left wrist, right wrist, and both tactors at the same time), the authors used only one level of tactile stimulation which activated both tactors. This

change from the previous study (Calhoun et al., 2003) was based on the significant difference in response time produced in solely the two-tactor activation condition. The auditory stimuli consisted of two different levels. Type 1 alerts were klaxon-sounds of 0.4 seconds, primarily at 487Hz, presented at 10.3dB. Type 2 alerts were klaxon-sounds with duration of 1.1 seconds, primarily at 500Hz, presented at 9.0dB. The first alert type, Type 1, was used across all alert conditions (baseline, +aural, and +tactile). The tactile alerts and the Type 2 auditory alerts were reserved for the critical alert conditions, while the caution alert conditions only made use of a visual alert and the Type 1 auditory alert. A list of these conditions is shown in Figure 2.2. The authors concluded that redundant non-visual alerts improved performance over using just the visual alerts. They also found that aural alerts were just as effective as tactile alerts, even when varying conditions of auditory load.

ALERT CONDITIONS		Visual	Redundant	
			Aural Cue	Tactile
Baseline	Caution	Yellow "C" on HUD & Yellow HDD text	Type 1	none
	Critical	Same, but red instead of yellow	Type 1	none
+2nd Aural	Caution	Same as Baseline	Type 1	none
	Critical		Type 2	none
+Tactile	Caution	Same as Baseline	Type 1	none
	Critical		none	wrists

Figure 2.2: Alert conditions for Calhoun et al. (2004, p. 138).

In another experiment, Aretz et al. (2006) had participants manually land a UAV. Participants used controls and visual displays that were similar to those found in the studies by Calhoun et al. (2003, 2004). However, participants were also presented vibrotactile feedback for altitude deviations through a tactor vest with four rows of tactors. Each of the rows represented a different level of deviation from optimal altitude during the approach. The top most row would vibrate intensely (200ms on, 100ms off, 66% duty cycle) if the UAV was 20 feet above the optimal glide slope. The second highest row would vibrate softly (100ms on, 600ms off, ~14% duty cycle) when the UAV was 10 feet above the optimal glide slope. If the glide slope deviation was below 10 feet, then the vest would not vibrate at all. Therefore, the magnitude of the glide slope deviation was coded by both the location of the vibrating tactors and the duty cycle. Higher deviation was mapped onto a longer duty cycle. A similar coding strategy was used for the bottom two rows for when the UAV was below the optimal glide slope, with lower locations and higher duty cycles representing larger glide slope deviation. The type of signal used to drive the tactors was not mentioned in the article. Aretz et al. (2006) found that tactile feedback changed how quickly participants were able to achieve good performance in the landing task. Even when operators were trained without tactile feedback, a tactile feedback system that was designed to be easily understandable could increase performance. It is important to note that this was an applied study that did not focus on how the tactile signals would be perceived at a basic level. The implications of basic tactile perception research on this tactile design will be discussed in Section 2.1.4.

2.1.2   Monitoring and Supervisory Control UAV Scenarios

In supervisory control scenarios, the participant's main task was not the manual control of the UAV through analog inputs. Instead, the UAVs in these simulations were largely autonomous and much of the flight was not controlled by the participants, whose main goal was to monitor the UAVs for abnormal behaviour and to make decisions about higher level mission goals. A pilot study by Donmez, Graham, and Cummings (2008) examined the use of haptic peripheral displays for the control of multiple UAVs. The Multiple Autonomous Unmanned Vehicle Experimental (MAUVe) test bed was used for this experiment. This experimental platform used a multi-monitor visual display, an over-the-head headset for auditory information, and an inflatable pressure vest and vibrating wristbands for haptic and tactile information. The goal of the experiment was to examine the differences between continuous feedback and threshold feedback haptic and tactile displays.

Two variables were chosen to be represented using the vest and wrist displays: late arrivals and course deviations. Late arrivals were displayed haptically through the inflatable vest. If a UAV was projected to be arriving late at a way-point, the vest was inflated to varying degrees based on the priority of the target. Only a few of the air bladders on the vest were inflated for low priority targets (4 bladders). Progressively more air bladders were inflated for the medium (6 bladders) and high priority targets (8 bladders). Each of the air bladders inflated to 20psi. In the continuous feedback condition, the vest would stay inflated until the participant responded to the late arrival or the UAV reached its target. However, in the threshold feedback condition, the entire vest would stay inflated for a 2000ms interval after the detection of the late arrival. The tactor wristband worn on the participant's right hand was used to represent information about the course deviations of UAVs. The five wrist tactors in the wristband were activated when course deviations occurred and had a frequency of 100Hz. No information was given regarding the amplitude or the type of waveform (e.g., sine, square, or saw-tooth) used to drive the tactors. In the continuous feedback condition, the tactors would stay on for 300ms per activation. As the deviation increased, the number of tactors activated was increased and the gap time between activations decreased. This led to a gradual increase in duty cycle for large course deviations. A graph with the number of tactors activated and gap times used can be seen in Figure 2.3. In the threshold feedback for course deviations, all the tactors would be activated for 600ms whenever the course deviation surpassed 10 degrees.
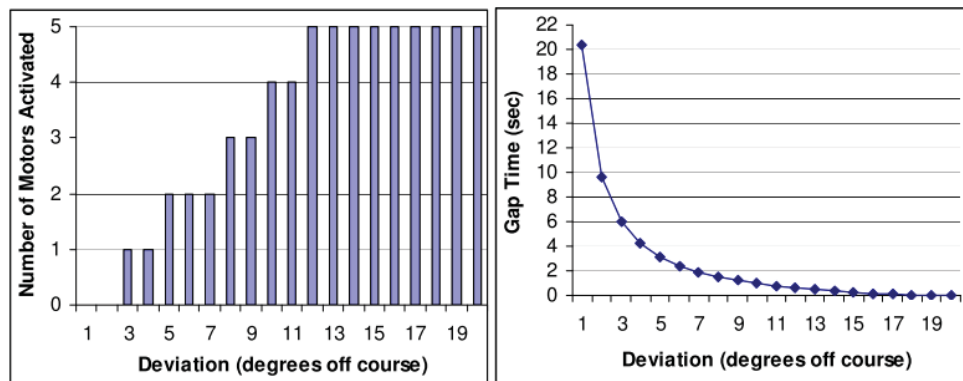

Figure 2.1: Number of motors activated and gap time between each activation as a function of UAV course deviation (Donmez, 2008, p. 9).

Continuous haptic feedback was found to produce significantly faster response times for course deviations, while threshold haptic feedback produced faster response times for late arrivals. No significant effects of feedback type were found for the secondary auditory loading task or for subjective measures of workload (as measured by the NASA Task Load Index; NASA-TLX). The authors suggest that continuous information, such as a deviation from the course, is best supported using continuous feedback, while a discrete event, such as a late arrival, is best supported using threshold feedback. The post-test feedback, gathered using the NASA-TLX, revealed that participants preferred the threshold feedback for course deviations over continuous feedback, even though threshold feedback produced slower reaction times. The authors state that this mismatch between the subjective and actual performance could be due to participants' annoyance at the continual buzzing of the wristband.

A similar study from the same lab was conducted by Graham and Cummings (2007) but used auditory peripheral displays instead of haptic displays. The same simulation, MAUVe, was used for this study, and the goal was again to examine the differences in continuous and discrete representation of variables. Late arrivals and course deviations were the variables that were chosen to be sonified, and for each of the variables a continuous and discrete sonification was developed. The continuous late arrival sonification was composed of discrete harmonic signals that were continuous played once the system predicted the late arrival of a UAV. The sonification continued until the operator responded to the late arrival event or until the UAV reached the way point. Graham and Cummings described the signals as:

> *"composed of five Formant filters that were applied to a mix of pink noise and the ambient signal. During the condition of no late arrivals, a baseline audio condition was generated with two filters set to 261.6Hz, two filters set at 329.4Hz, and one filter set at 392.0Hz (a major C triad with extra balance in the root and third). If it was late to a low priority target, a signal was generated with two filters set to 261.6Hz, two filters set at 311.1Hz, and one filter set at 392.0Hz (a minor C triad with extra balance in the root and third). If it was late to a medium priority target, a signal was generated with three filters set to 293.6Hz and two filters set at 415.3Hz (a tritone interval with a D root). If the UAV was predicted to be late to a high priority target, a signal was generated with three filters set to 369.9Hz and two filters set at 523.25Hz (a tritone interval with an F# root). As the priority increased, the pink noise mix also increased, from 0.25 for the baseline, to 0.7, 0.8, and 1.0 for the three priority levels"* (Graham and Cummings, 2007, p. 8).

The discrete late arrival sonification used a signal tone with a fundamental frequency of 415Hz which played for 18ms. This signal was used whenever the system predicted the late arrival of one of the UAVs.

The continuous course deviation sonification was created using:

> *"comb filters that were applied to a mix of pink noise and the ambient signal…. The mix ranged from 0.2 pink noise for low deviation to 0.9 pink noise for high deviation. The comb filters had a base delay of 0.2ms, with a 50 percent each mix of the base signal and a feed forward delay. The delay values were then oscillated to create a periodic signal. Because this was a continuous audio scheme, it played continually to provide an auditory image of UAV path position. As a UAV drifted further off course, the frequency of*

oscillation of the comb filter delay decreased from 17Hz to 4.5Hz, and the depth of oscillation increased from 0.2ms to 0.7ms, thus changing on a continual scale" (Graham & Cummings, 2007, p. 8).

The discrete course deviation alert made use of a single tone with a fundamental frequency of 1000Hz which played for 8ms. This signal was used whenever a UAV deviated from the planed course. The results were very similar to the haptic study (Donmez et al., 2008); continuous representations were best suited for continuous data and discrete representations were best suited for discrete data.

2.1.3   Manual Control UAV Simulations

In this section we examine the auditory and tactile cues used in 5 different UAV simulation environments. The multimodal stimuli were used in a wide variety of tasks and situations. This suggests that there are many possibilities for the use of auditory and tactile cues within the domain of supporting UAV autolanding. Auditory and tactile cues and displays were used in both situations where an operator was required to manually fly a UAV using an analog control, and when the operator was only responsible for monitoring the overall status of the UAV. The following table contains the different types of codes used for each modality.

Table 1: Coding used in UAV simulation studies.

Modality	Coding Used	Variables Coded	Number of Levels or Range	Studies
Tactile	Spatial location, horizontal rows on a vest.	Glide slope deviation (horizontal deviation).	5	Aretz et al. (2006)
	Duty cycle of vibrotactile stimuli.	Glide slope deviation (horizontal deviation).	5	Aretz et al. (2006)
		Course deviation.	10+	Donmez et al. (2008)
	Number of tactors activated.	Course deviation.	5	Donmez et al. (2008)
	Tactors activated.	Course deviation occurred.	1	Donmez et al. (2008)
Haptic	Number of air bladders inflated.	Priority level of a late-arriving UAV.	4	Donmez et al. (2008)

	Haptic vest inflated.	UAV late arrival detected.	1	Donmez et al. (2008)
Auditory	Klaxon sounds.	Warnings.	1	Calhoun et al. (2003)
		Alert conditions (warnings and information queries).	2	Calhoun et al. (2004)
	Different musical chords and intervals.	Priority level of a late-arriving UAV.	4	Graham and Cummings (2007)
	Increased mix of pink noise.	Priority level of a late-arriving UAV.	4	Graham and Cummings (2007)
		Course deviation.	Range from 0.2-0.9 as deviation increased (number of levels unknown).	Graham and Cummings (2007)
	An auditory beep.	UAV late arrival detected.	1	Graham and Cummings (2007)
		Course deviation detected.	1	Graham and Cummings (2007)
	Comb filter delay oscillation frequency.	Course deviation.	Range from 17Hz-4.5Hz as deviation increased (number of levels unknown).	Graham and Cummings (2007)
	Comb filter delay oscillation depth.	Course deviation.	Range from 0.2ms-0.7ms (number of levels unknown).	Graham and Cummings (2007)

Overall, these studies demonstrated that certain coding methods were better suited for certain applications. Donmez et al. (2008) and Graham and Cummings (2007) both showed that continuous coding methods were best suited for continuous data, while discrete coding methods were best suited for discrete data. While this type of coding is possible with some auditory characteristics, most of the tactile codes were not continuous. This was especially true for tactile spatial codes which relied on a small set of tactors. However, the Donmez et al. (2008) study also showed that participants preferred threshold (discrete) feedback over continuous feedback. This could be attributed to lower perceived workload, because participants were not required to discriminate between many different levels in threshold conditions. While this was true for the monitoring task used in the Donmez et al. (2008) study, continuous stimuli may be better suited for supporting tracking tasks where participants are required to manually control and compensate for deviations.

None of the codes used caused decreased performance when compared to the baseline cases, which were often based solely on visual feedback. Duty cycle was one code that was used in multiple studies as a method for showing increased magnitude of a monitored variable. Typically, higher duty cycles were mapped onto larger magnitudes. For instance, Aretz (2006), mapped higher magnitude glide slope deviations to a 66% duty cycle, compared to only a 14% duty cycle for the lower magnitude glide slope deviations. Aretz (2006) also used spatial codes to represent spatial deviations, which could be an intuitive method for coding spatial information. Participants found that tactile feedback changed how quickly they were able to achieve good performance in the landing task. In the Graham and Cummings (2007) study, larger magnitudes of course deviation and higher priority targets had larger amounts of pink noise mixed into the auditory sonification. This suggests that "noisier" sonifications are mapped onto data of higher magnitudes and intensities. Because higher intensity data requires a more immediate response, designers may wish to code urgent information with increased amounts of noise.

In conclusion, while there are still very few studies that have used auditory and tactile cueing in UAV simulation environments, we can draw from many of these studies to build a foundation for the creation of our own multimodal designs. It will be important to ensure that data that is continuous will be mapped onto continuous display characteristics and that discrete display characteristics are used to represent discrete data. Spatial location, duty cycle, the amount of noise mixed into a signal, frequency, and magnitude are all codes that can be used in the design of our signals.

2.1.4   Perceptual Issues of Tactile Perception

In the previous section, we reviewed a number of studies that have made use of auditory and tactile interfaces to present information during UAV simulations. However, one drawback of many of the studies discussed was that they did not make use of current research on the perceptual issues of tactile perception. In Giang et al. (2010), a number of issues related to the perception of tactile stimuli including spatial acuity, adaptation, and habituation were discussed. In this section we review the current literature on tactile perception with regards to the task of presenting course deviation information. We will focus on the merits and drawbacks of some of the coding methods discussed in Section 2.1.

In tactile displays there are a few major issues that could have large impacts on the design of the displays. In this section we will discuss three of these factors: spatial acuity, adaptation, and habituation. These factors were chosen because they impact the physical layout of tactor based tactile displays. Spatial layout and tactile pattern design are two design parameters that are very easy to manipulate in the design of tactile vests and have much more perceptible characteristics than differences in frequency, amplitude, and waveform. Spatial acuity refers to an individual's

ability to differentiate between two different tactile stimuli when they occur at different spatial locations. Spatial acuity varies across the body and is highest for the fingers, lips, and genitals (Cheung et al., 2008). Spatial acuity on the torso is much lower, and for vibrotactile stimuli, it is relatively uniform over the entire torso. In this region spatial acuity is approximately 2–3cm for vibrotactile stimuli. This acuity is better for horizontally oriented arrays located in line with the spine and navel and is approximately 1 cm in these regions (Van Erp et al., 2005).

Within tactile displays, spatial acuity impacts where tactors should be located. In a tactile vest, spatial location could be used to code information (e.g., Aretz et al., 2006) study. When this type of coding is used, it is important to ensure that users are able to differentiate between the different spatial locations by ensuring that tactors are not placed too closely together. Aretz et al. (2006) did not indicate the inter-tactor spacing between rows. However, as mentioned previously, the spatial acuity on the torso is approximately 2-3 cm. Therefore, inter-tactor spacing should be at least 3 cm for proposed tactile vest configurations. Spatial acuity is important when different tactor locations must be differentiated. However, groups of tactors that represent a single grouping (such as the rows within the Aretz et al. (2006) study) may not need the same degree of inter-tactor spacing.

Adaptation is another important factor in the design of tactile displays. Adaptation refers to "a change in the percept of a stimulus after prolonged stimulation." (Cheung et al., 2008, p. 2-8) In situations when the tactor vest is used for monitoring a continuous variable, care must be taken to reduce the effects of adaptation. Adaptation does not happen across frequency bands (Cheung et al., 2008), so one method for preventing adaptation is by changing the tactor's frequency. However, this may not be as applicable in the design of tactile displays because frequency is not an ideal coding parameter as suggested by our previous literature review (Giang et al., 2010). Another method suggested by Cheung et al. (2008) was the use of appropriate duty cycles to combat adaptation. A duty cycle with an off cycle three times as long as the on cycle was used as an example (i.e., duty cycle of 25%). In the Aretz et al. (2006) study and the Donmez et al. (2008) study, course deviation was coded using tactor duty cycles. Specifically, the Aretz et al. (2006) study used an "intense" duty cycle of 66% and a "soft" duty cycle of 16%. The Donmez et al. (2008) study used a variety of different duty cycles that gradually increased as the course deviation increased. For both these studies, only high degrees of course deviation would result in duty cycles that could possibly suffer from adaptation. Also, since both of these occurred in studies that had manual control of the UAV, the course deviation would likely be corrected before adaption would occur. Hollins et al. (1990 as cited by Cheung et al., 2008) state that the time constant of adaption is approximately 2 minutes. Thus, if high course deviations are corrected in less than 2 minutes, adaptation may not occur.

Habituation is another phenomenon that could occur when tactile patterns are presented to the user. Unlike adaptation, habituation does not degrade sensory sensitivity. Instead, a sensation that has habituated no longer draws attention to itself (Cheung et al., 2008). Cheung et al. (2008) state that even duty cycles that can avoid adaptation may still fall victim to habituation. Thus, any continuous signal will likely be habituated to over a long duration of exposure. The authors suggest that "null zone conditions", conditions that indicate nominal behaviour, should be created where no stimuli is presented. This occurs in both Aretz et al. (2006) and Donmez et al. (2008), where course deviations of 0 are coded with no tactor activations.

In conclusion, current research on tactile perception provides some guidance on the design of layouts for tactile vests. For our designs, inter-tactor spacing of 3 cm (tactor edge to tactor edge)

should be used. In addition, duty cycles of 3 off: 1 on could be used to prevent adaptation. Higher duty cycles could still be used if they are not on for longer than 2 minutes. Higher duty cycles may also lead to higher perceived intensity due to temporal summation, and may be appropriate for high urgency situations.

2.2   Proposed Auditory and Tactile Displays

The review of the relevant literature on multimodal displays in UAV simulators demonstrates that there are many possibilities for implementing auditory and tactile displays for the current UAV autoland scenario. Multimodal signals could provide information on monitored variables, alerts, warnings, or they could help provide information to guide the operator's attention. Through discussions and meetings with the scientific authority and with a current civilian pilot, a number of proposed displays were developed for displaying attitude upsets, engine RPM, and for displaying various warnings.

2.2.1   Pattern Displays vs. Symbolic Displays

For the tactile displays proposed, it may be possible to display information through tactile symbols. However, little research has been conducted on how efficiently individuals are able to differentiate between various symbols created with tactors (Self, Van Erp, Eriksson, & Elliott, 2008). Yanagida et al. (2004) demonstrated that letter recognition with tactors was relatively successful (87% correct letter or number recognition). However, it should be noted Yanagida et al. (2004) did not ask participants to perform any additional tasks. In high workload situations, where a user is forced to perform additional tasks, these results may not hold true and we may observe a decline in accuracy.

In another study by McKinley et al. (2005), three different tactors were used to present enemy, unknown, and friendly aircrafts to pilots. The location of the tactors on the vest indicated the spatial location of the target aircrafts relative to the subject's aircraft. The results of this study indicated that the differentiation between the various tactors was not an easy task. Also, the individual's familiarity with the necessary set of symbols affected accuracy during the pattern recognition process. Thus, the size of the symbol set and the training given to operators become critical factors.

Another important factor is the type of data that is being conveyed. In our baseline GCS interface, attitude information is conveyed continuously through the UAV's camera and through the use of visual displays. System fault information, on the other hand, is presented in discrete units. Due to continuous or discrete characteristics of the information being conveyed, tactile patterns would be more appropriate for continuous information such as attitude. Tactile symbols would be better at presenting discrete warning information.

2.2.2   Attitude Upsets

One of the critical variables that UAV operators are responsible for monitoring is the attitude of the UAV. The UAV's attitude is composed of its roll, pitch, and yaw. Deviations from the UAV's proposed attitude can lead to an inability for the UAV to land safely. The tactile vest was chosen as the primary method for presenting attitude upset information to the UAV operator. Roll, pitch, and yaw are all spatial variables, and deviations in any of these dimensions could easily be shown using intuitive spatial representations on the tactile vest in a manner similar to that used by Aretz et al. (2006). However, we also provide suggestions for an auditory implementation of many of the tactile displays as a way of providing redundant or supplementary information.

Four different types of displays were developed to show attitude upsets: roll, pitch, yaw, and a combined attitude upset measure. For the individual roll, pitch, and yaw displays, it was important to show both the magnitude of the deviation and the direction of the deviation. For the combined attitude upset measure, magnitude was determined to be the sole factor which was important to display.

As mentioned in our previous literature review (Giang et al. 2010), tactile patterns and perceptions of apparent movement can be generated by sequentially activating a series of vibrotactors placed on the skin (Cholewiak & Collins, 2000). Patterns have been used to intuitively present information regarding orientation or direction of external events. Given the success of such patterns, we feel that patterns could also be used to show attitude information to UAV controllers. We believe using tactile patterns should reduce the amount of error and processing time for understanding the UAV situation by the operators.

Another important issue when designing for attitude upsets is whether or not directionality of the deviation is necessary information. When directionality is included, the user is provided with additional information about the type of deviation that is occurring, and may be able to better grasp the current situation of the UAV. For example, a UAV that is experiencing additional roll in the direction of a turn is probably suffering from a different problem than a UAV that is experiencing roll in a direction that is opposite that of the intended turn. However, directionality also increases the complexity of the tactile and auditory signals. This may result in patterns that are more difficult to interpret and learn. Also, just the knowledge that attitude upset is present may result in the participant checking the visual displays, which may be a better way for communicating detailed information. Due to these issues, we felt that during situations where we were designing for more detailed displays (i.e., separate displays for attitude upsets), directionality was still an important characteristic to portray. However, for aggregate displays, directionality was less important.

2.2.2.1   Proposed Method for Displaying Roll

A suggested tactor configuration for displaying the angle of the UAV's roll is depicted in Figure 2.4. This configuration requires 21 tactors and uses 5 activated tactors per level. The tactor configurations can be positioned either on the front or back of the vest.
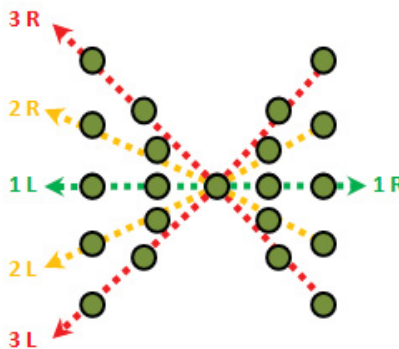

Figure 2.4: Suggested tactor configuration for roll presentation.

This tactor configuration presents information through moving tactile patterns. It is possible to present three completely separate levels of roll through the configuration provided above. The mapping of degrees of roll deviation to the different levels is a task that must be accomplished at a later stage. The first level of roll deviation is presented by activating the tactors located on the green dotted line. For example if the UAV's roll deviation is less than 20 degrees to the right, we can show this by activating the tactors aligned on the right side of the green dotted line, indicated by "**1 R**." Higher levels of roll deviation can be shown by activating the tactors aligned on the yellow and red dotted lines. For example if the UAV's roll deviation is more than 20 degrees and less than 40 degrees to the left, we can show this by simultaneously activating the tactors aligned with the yellow dotted lines designated "2 L."

2.2.2.2 Tactor Activation Sequence for Displaying Roll

The simultaneous activation of two vibrotactors located close together causes the sensation of only a single point between the two tactors (apparent location). This point shifts continuously toward the vibration with higher intensity (Scherrick, Cholewiak, & Collins, 1990). We can apply this phenomenon to our proposed method, to remove the feeling of discrete levels of UAV roll deviation on the tactor vest. For example, when a UAV's roll changes from "1 R" to "2 R," as in Figure 2.5, the tactor activation sequence would be as follows:

1. Reduce the vibration amplitude of the "1 R" tactors from 100% to 50% of their maximum value and increase the vibration amplitude of the "2 R" tactors from 0% to 50% of their maximum value.

2. Reduce the vibration amplitude of the "1 R" tactors from 50% to 0% of their maximum value and increase the vibration amplitude of the "2 R" tactors from 50% to 100% of their maximum value.

By using this activation strategy we can provide sensations of apparent locations between the actual locations of the tactors. This may aid in decreasing the confusion in understanding the UAV's current roll deviation by providing more perceivable levels of roll information.
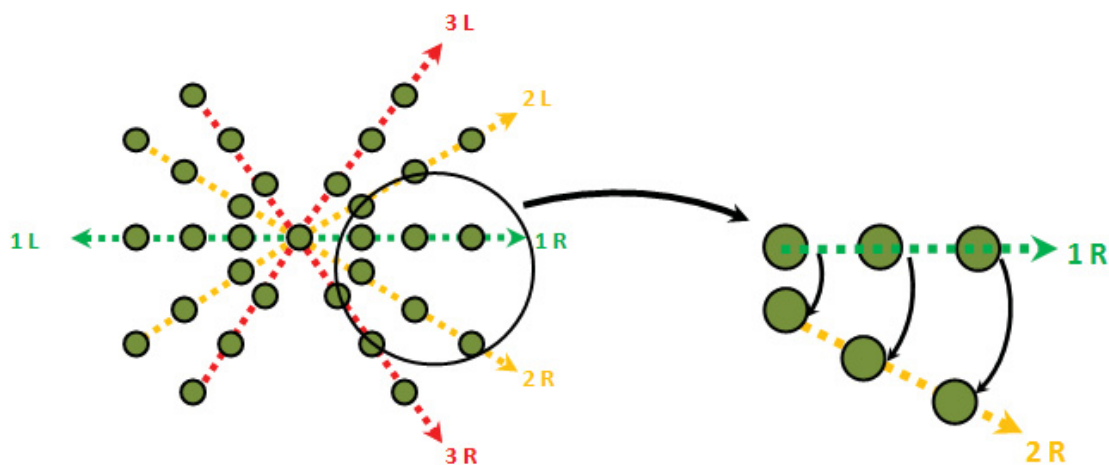

Figure 2.5: Tactor activation sequence for roll display.

2.2.2.3   Auditory Display for Presenting Roll

Our auditory roll signal is very similar to the one we proposed for the tactile roll signal. The main goal of the roll display (for both the auditory and tactile displays) is to show rapid changes in attitude, especially ones that oscillate. To accomplish this we need to show both the magnitude and frequency of the changes. In tactile displays, frequency information is limited by how quickly we can change the tactile patterns to show the oscillations and how well the operators can detect these changes. During high turbulence (as might be experienced during wind shear), these changes may be beyond what our tactor display is able to display. Thus, we propose that a redundant auditory signal be used in conjunction with the tactile display.

The auditory signal will provide more detailed information about the frequency of roll changes (how often the roll has switched directions). Our auditory signal will provide a beep every time the roll changes directions. During very turbulent periods the rate of the auditory beeps will provide a better measure of the severity of the turbulence. This information will be synergistic with the magnitude (and low resolution frequency) changes shown using our tactor display.

However, we can also modify the auditory component to show magnitude information by changing the intensity (loudness) of the auditory signal as the magnitude increases. Because roll is a continuous variable, the changes in intensity will also be continuous. However, 3D auditory displays may not be practical for implementation for this study. Thus, we decided that the direction of the roll should be represented by the changing the ear to which the auditory signal is presented (using stereo headphones). Roll to the left would be signalled with presentation to the left ear and roll to the right would be signalled with presentation to the right ear.

2.2.2.4   Proposed Method for Displaying Yaw

The effectiveness of a vibrotactile torso display as a countermeasure to spatial disorientation was investigated by Van Erp et al. (2006). In this study, participants wore a vibrotactile display vest which consisted of 24 columns of 2 vibrotactors while seated on a rotating chair. This vibrotactile display was designed to help participants recover from spatial disorientation. The results of this experiment demonstrated that a vibrotactile display can assist operators as they recover from loss of spatial orientation.

Inspired by the Van Erp et al. (2006) experiments, our display indicates the UAV's yaw (heading) deviation using a simple tactor configuration. As shown in Figure 2.6, a row of tactors, consisting of five C2 tactors, is placed in the frontal region of the tactor vest. The UAV heading can be displayed by sequentially activating the vibrotactors along the observer's chest or abdomen along the horizontal plane. In this method, the vibrotactile signal moves in the same direction of the UAV's yaw deviation. The tactor located on the midsagittal plane of the torso acts as the null point in this configuration.

It should be noted that this display is only activated when the UAV's heading deviates from its desired heading. For example, if the UAV is programmed to travel from Point A to Point B, it has to hold a specific heading. If for any reason (such as turbulence or wind-shear) the UAV's heading deviates from its desired value, the yaw display can be activated to show the intensity of the yaw divergence. This is illustrated in Figure 2.7.
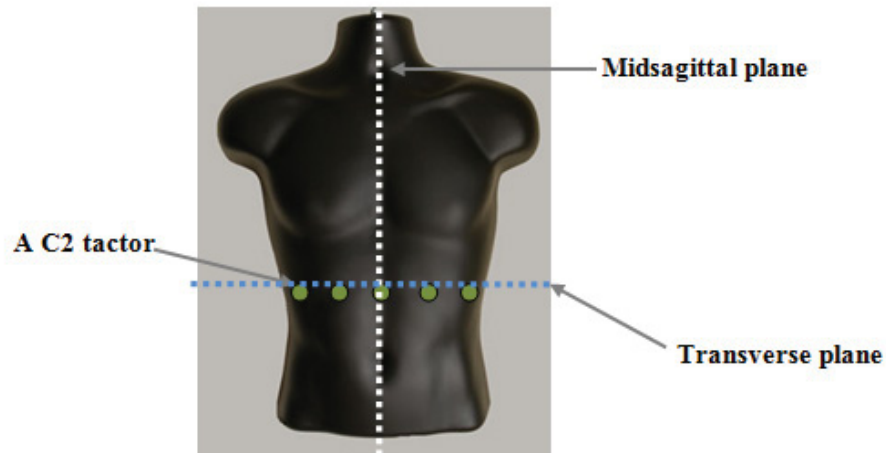
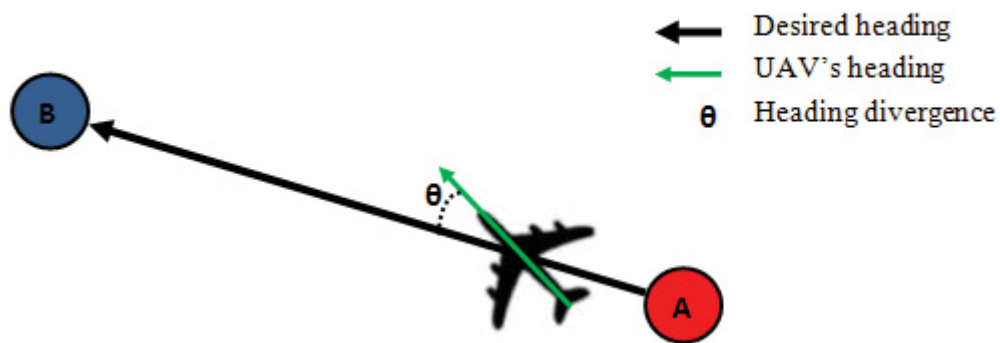*Figure 2.6: Suggested tactor configuration for yaw presentation.*

Figure 2.7: UAV's heading and desired heading.

2.2.2.5 Proposed Method for Displaying Pitch

Our suggested configuration for displaying pitch is very similar to the configuration used in the yaw display. As can be seen in Figure 2.8, this configuration makes use of a vertical column of five C2 tactors in the frontal region of the tactor vest. The UAV pitch can be displayed by sequentially activating the vibrotactors aligned along the observer's midsagittal plane. In this method, the vibrotactile stimulus moves in the same direction as the UAV's pitch deviation. The middle tactor (the third of five tactors) acts as the null point in this configuration.
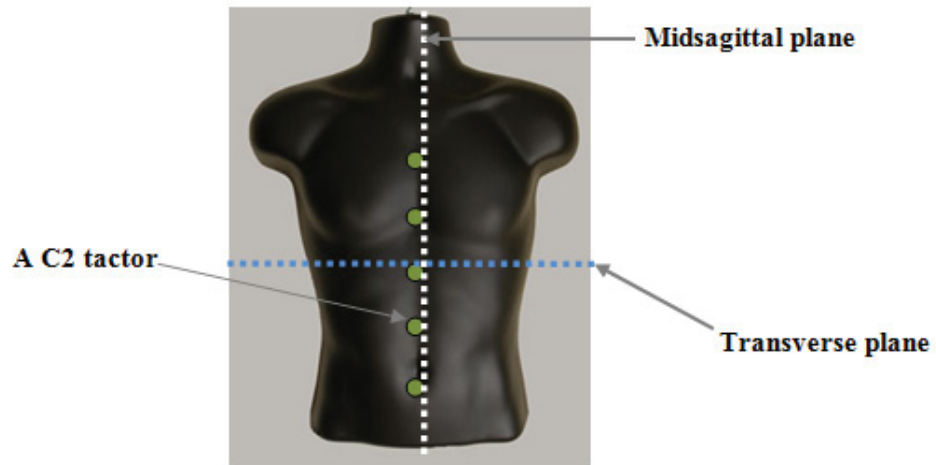
Figure 2.8: Suggested tactor configuration for pitch presentation.

Similar to the yaw display, this display is only activated when the UAV's pitch angle deviates from its desired pitch angle. For example, during a UAV recovery, the UAV may need to increase or decrease its pitch to land safely. As shown in Figure 2.9, if for any reason (such as turbulence or wind shear) the UAV's pitch angle deviates from its desired value, the pitch display can be activated to show the intensity and direction of the pitch angle divergence.
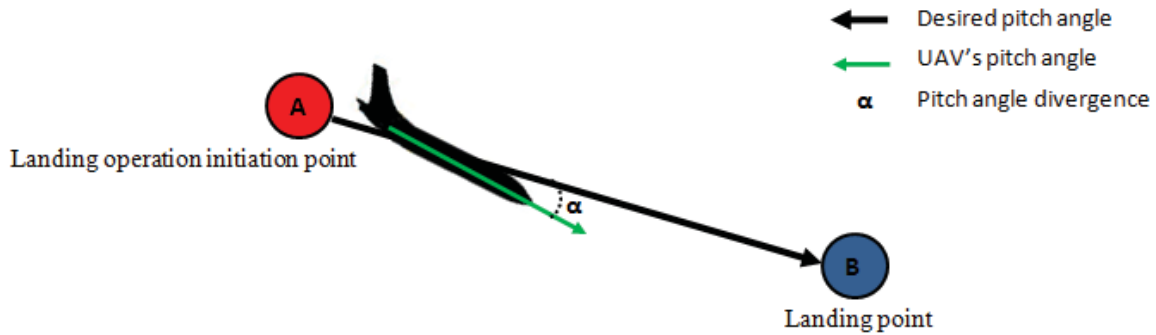

Figure 2.9: UAV's pitch angle and desired pitch angle.

2.2.2.6   Combination of Yaw and Pitch Displays to form Yaw-Pitch Display

In the last few sections we introduced and described the relevant tactor configurations to present yaw and pitch through the tactor vest. We believe that we can combine these configurations to construct a more complex tactor display. We call it a yaw-pitch display.

As Figure 2.10 shows, the yaw-pitch display would be constructed of a 5×5 tactor matrix. This tactor configuration is capable of showing yaw and pitch intensity concurrently. The intensity of yaw can be presented by activation of tactors along the horizontal axis and the intensity of pitch can be displayed by activation of tactors along the vertical axis. Therefore the yaw intensity would be presented in terms of the distance between the activated tactor and the midsagittal plane

of the body, and the pitch angle would be presented in terms of the distance between the activated tactor and the transverse plane of the torso.
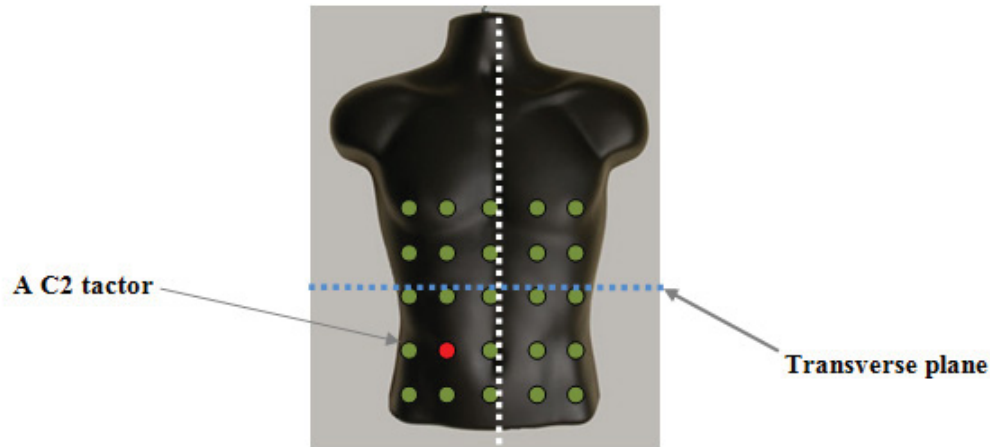

Figure 2.10: Suggested tactor formation for pitch and yaw display.

For instance, if the tactor indicated in red is activated (shown in Figure 2.10), this would represent a situation in which the UAV has a yaw deviation to the right and downwards pitch deviation.

The use of two tactile patterns in combination is one that has not been reported in the literature and this combination may reveal many questions regarding how efficiently operators can detect the two patterns concurrently. We feel that the patterns provide information which is sufficiently different and intuitive, that the operator would be able to make use of both displays at once. This should, however, be investigated further.

2.2.2.7   Aggregate Attitude Upset Display

In the previous sections we explored attitude displays that would provide information about flight dynamic parameters that could be presented independently and concurrently. The roll display was designed such that it could be mounted on the back of the vest, while the pitch-yaw displays could be mounted on the front side of the vest. Therefore, it may have been possible for the UAV operator to perceive the intensity of the roll, pitch, and yaw using the as individual indicators of flight dynamics though the vibrotactile vest.

However, there are other methods for presenting the magnitude of the UAV's deviation from its desired direction using the tactile vest. One possible method is to use the vibrotactile display to show the general deviation of the UAV from its desired track. Using this method the operator would not be able to differentiate between the intensity of the yaw, pitch, and roll deviations. However, they would be presented as an aggregate indicator of attitude upset. Therefore, in this type of display the UAV operator will only have a general perception of the UAV spatial orientation. Such a display may provide enough information to the UAV operator to allow them to make an informed judgement about whether the UAV is able to land.

The following are two proposed methods for conveying this aggregate attitude indicator.

2.2.2.7.1 Column of Tactors

The suggested tactor configuration for a column of tactors display is depicted in Figure 2.11. As the figure illustrates, the configuration of the vibrotactors in this display is very simple. Eight C2 tactors are placed in a vertical row along the midsagittal plane of either the front or back of the vest to form a column.
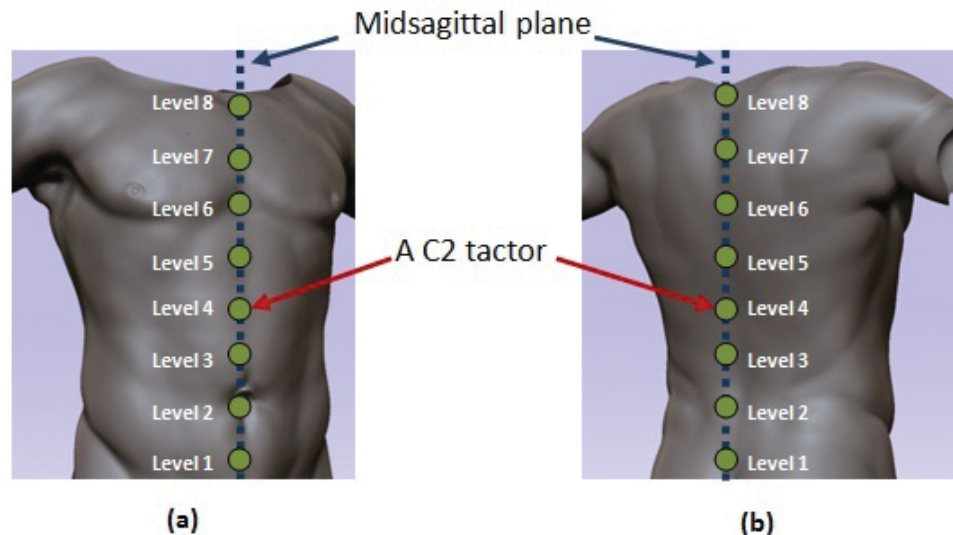

Figure 2.11: Column of Tactors

Studies have revealed that spine and the navel can work as natural anchor points and observers are more capable of correctly detecting stimuli near these points (Cholewiak et al., 2004; Van Erp, 2005). Therefore, the tactor column should be placed in such a way that it aligns to the observer's midsagittal plane. Based on the activation sequence of the C2 tactors, there are two methods for showing the aggregate attitude upset using a column of tactors.

Activation in Sequence

In this method of activation, the vertical distance of the activated tactor from the body's pelvis plane (the bottom of the torso) represents the magnitude of the attitude upset. For example when the magnitude of the UAV's deviation changes from Level 1 to Level 2, the Level 1 tactor is deactivated and the Level 2 tactor is activated. This would correspond to an increase in the UAV's attitude upset. One possible weakness of this display is the ability for UAV operators to discriminate between the different levels of the display. The operators may not be able to clearly and easily recognize the exact location of the vibration on their torso when there is only one tactor activated.

Equalizer activation

In this type of activation, the number of activated tactors and the location of the upper-most activated tactor represent the magnitude of the deviation. Using this method, the tactor located on the lower level is not deactivated when the attitude upset increases from one level to another. For example, when the UAV's attitude upset is at Level 3, all of the tactors on lower levels (Level 1 and Level 2) are also activated. Similarly, when the attitude upset increases to the next level, all

the tactors up to that level will stay activated. One metaphor for this type of tactor display functionality would be the graphical equalizer display in electronic audio devices. The length of the vibrating column represents the intensity of the UAV's deviation from its desired path. One advantage of this type of activation is that operators are not relying solely on the location of the vibrating tactor because the number of tactors vibrating acts as a redundant cue. This could also potentially convey some degree of urgency as the net tactile stimulus increases. One disadvantage would be possible adaptation or annoyance because some tactors (the lower levels ones especially) would be on for much longer durations as the UAV's attitude upset increases.

2.2.2.7.2   Uni-centred Circles of Tactors

The second proposed display for showing an aggregate attitude upset can be seen in Figure 2.12.In this configuration tactors are located in uni-centred circles.
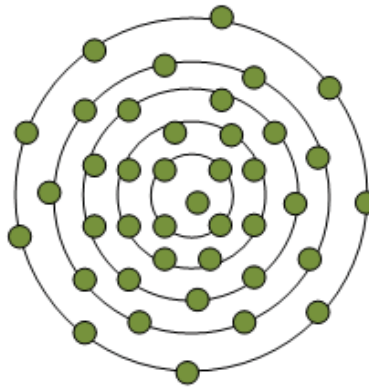
Figure 2.12: Tactor formation for the uni-centred circles of tactors.

In this type of display, the tactors which are located equidistant from the center of the circle are activated simultaneously and represent the various levels of the display. The size of the circles represents the magnitude of the deviation of the UAV from its desired path. The larger the circle is, the higher the represented attitude upset is. This design uses the location of the tactors (represented by the distance of the tactors from the center) and the number of tactors as ways of conveying magnitude information. Other possible variations of this design are square arrays of tactors or other shapes.

It is worth noting that the magnitude information presented may not seem to increase linearly because the number of tactors activated is not increased at a linear rate, but rather as a function of area covered by the tactors used. There is currently little research literature to indicate whether this method of increase would result in a perceptual effect of a squared magnitude or a near linear increase in magnitude. We know that in a visual display, biases can be introduced when linear variables are mapped to non-linear graphics (Tufte, 1997 provides good examples of this). This effect may not be as evident in tactile displays, due to the reduced and varying sensitivity of the tactile display zone on the body. If the effect occurs however, the display may need to be modified place the different levels more appropriately, based on the attitude upset.

2.2.2.8   Advantages and Disadvantages of Aggregate Attitude Displays vs. Separate Attitude Displays

In this section we will briefly discuss the various benefits and drawbacks of the ideas presented above, compared to those which would allow the presentation of individual attitude upsets. Both

of these methods could serve a role in alerting the operator to re-examining the visual interface in off-nominal situations. The choice of a single solution would be highly dependent on the training, experimental tasks, and kinds of task switching behaviour we expect from our participants.

One of the strongest advantages for the use of an aggregate attitude upset display is the simplicity. One danger of tactile displays, and multimodal interfaces in general, is overloading the operator with information. During the 2010 Human Factors and Ergonomics Society Annual Meeting, the discussion panel on tactile displays emphasized that the bandwidth of tactile displays is limited, and thus, simple and important messages may be best suited for tactile displays. An aggregate attitude upset display would alert the operator to any deviation to the UAV's flight path, while not requiring the operator to integrate different pieces of information to come to the conclusion that the UAV has veered off its intended path. Thus, this type of display would alert the operator to glance back at the visual displays and gather further information.

There are two main disadvantages for the use of the aggregate display. The first is the need to have some sort of formulation to generate a single value for attitude upset based on roll, yaw, and pitch information. In most aircraft, attitude indicators (such as http://en.wikipedia.org/wiki/Attitude_indicator) show pitch and roll as two separate dimensions on a display. Heading is shown with other instruments. From our research, there are no standard methods of mapping the three attitude measures into a single aggregate value. While there are some examples from attitude control systems, the equations are relatively complex due to the need to combine three angular measures compared against a dynamic frame of reference. If an aggregate display were chosen for implementation, we would need to formulate our own mathematical solution to calculate attitude. This method could be advantageous because we could then design a formula that would be most indicative of the types of phenomenon we are designing our display to be sensitive to (wind shear and turbulence). A simple example of a formula would be to normalize each of the separate attitude upset measures (roll, pitch, and yaw) and to sum them into one variable. However, any formulation will require some degree of fine tuning and require exploration of various attitude equations to develop the most effective representation for a human operator. Some generalization of the end results would be lost as our experimental results would be dependent on a unique computation of the general attitude variable. The argument could also be made that our computed equation introduced bias by making certain parameters of our experimental task more salient.

The second major disadvantage of an aggregate display would be the lack of situational awareness information that the tactile display would provide. Depending on the type of formula used, many different inputs of pitch, yaw, and roll would provide the same aggregate value. Operators would not be able to differentiate between these values. In addition, because the aggregate display would be less informative of flight dynamics overall, it may provide very little benefit over the use of an attitude upset alarm. Operators may choose to glance at the visual display anytime the tactile display was activated. This may occur regardless of the degree of severity of the attitude upset because the tactile display itself does not provide any further information. Separate attitude displays, on the other hand, may provide operators with greater levels of information. Greater information could allow the operator to delay switching away from a secondary task if they deem it is unnecessary due to the additional situation awareness created by the separate displays.

In the case of separate attitude displays, the display can be simplified by choosing to only use one of the attitude dimensions (e.g. pitch or roll). The variable remains ecologically compatible with

the flight dynamics of the UAV and is a variable that pilots understand well from their training. While the display still needs to be tuned to set the mapping correctly, the variable should be mapped in such a way that it requires no computation. The directional information available in the display allows the pilot to extract more information than simply magnitude, which should improve situation awareness.

2.2.3 Warnings and Alerts

Other possible variables that could be displayed using auditory and tactile stimuli are the warnings and alerts that are currently shown visually on the UAV interface. These alerts cover a wide variety of situations that the UAV may encounter. Some are non-critical and provide information such as "landing gear deployed," and some are critical and require immediate response such as "engine failure." We developed two proposed warnings and alerts for the multimodal interface. Both of these displays can be presented through either auditory or tactile stimuli, and presentation methods in both these modalities are described below. As suggested by prior work (Donmez, Graham, & Cummings, 2008), continuous displays are better at presenting continuous information and threshold displays are better are presenting discrete data. Therefore, the use of warnings and alerts are better for providing awareness of discrete events. Thus, it is our proposal that the multimodal alerts be used for monitoring system faults that are currently represented using discrete visual alerts in the baseline GCS.

2.2.3.1 Simple Alert

Our first proposed solution is to map each of the system fault warnings (e.g., high engine revolutions per minute (RPM) warnings, low engine RPM warnings, or high engine temperature warnings) to a simple auditory or tactile alarm. The purpose of this alert would be to direct the operator's visual attention back to the GCS interface so that they can gather further information. Operators can make use of this information to minimize the amount of time spent monitoring the GCS interface by allowing for the alert to prompt when they should shift their attention. This, in turn, should allow the operator to spend more time on the secondary task, leading to higher accuracy and faster response times.

From the information currently available about system faults in the simulator, we did not think that different alarm priorities were required. Thus, we envision a simple alert that will only sound once (when the GCS first presents the visual alert). The auditory alert would consist of a short duration (~0.2s) beep, similar to the discrete alerts used in Graham and Cummings (2007). The tactile alerts would make use of the tactors placed on the thighs and they would also vibrate for only a short duration (~0.2s). The intensities of the auditory and tactile signals would be constant throughout the duration of the alert.

Findings from Calhoun et al. (2004) suggest that both auditory and tactile redundant cues would be effective at improving performance over just a visual cue. Therefore, we think that either of the cues could work and the best solution would be dependent on other multimodal stimuli. In our experiment, the faults are always reliable, hence optimal behaviour would be to only inspect the GCS interface when alerted by the auditory and tactile alert (or when the operator feels like there are detrimental environmental conditions which are not presented through these alerts). Thus, an operator will reach optimal performance when they become completely reliant on these alerts for keeping track of system faults.

2.2.3.2 Complex User-Aware Alert

Our second proposed alert is one that will make use of an eye-tracking system to gain some awareness of what the operator is currently doing. In our experiment, the workload of the secondary task is constant, therefore there is little opportunity to switch between tasks (i.e. switching during low workload periods and ignoring alerts during high workload periods). However, it may be prudent to design an alert system which can be ignored by the operator when they prioritize higher workload tasks. Thus, we propose an alert that will slowly increase in intensity from when the fault first occurs, until the operator finally deals with the fault (either through the concern or abort buttons). Whenever the operator glances at the GCS console, the intensity of the alert will be reset to the starting point, but will continue to grow until the situation is resolved. We have decided to use the temporal rate of the alert as a method for manipulating the intensity. This is because the speed of an alarm was found to have the greatest effect on the perceived urgency of an auditory stimulus (Hellier & Edworthy, 1999).

The auditory alert will consist of a short duration (~0.1s) beep, which will increase in rate as the duration of the alert increases. The alert will have an initial rate of 1 repetition per second and will reach a maximum intensity of 8 repetitions per second within 10 seconds from the beginning of the alert. These values may need to be further refined after pilot testing. The tactile alert will follow a similar pattern. If the eye-tracker detects that the operator has looked at the GCS interface, then the intensity of the alert will be reset to its initial state. The advantage of using a display such as this is that it allows the operator to prioritize their task switching while staying aware of how long they have ignored the primary task.

2.2.4 Engine RPM

In the current GCS interface, high and low engine RPM are shown as discrete warnings through a visual display. However, the use of auditory and tactile displays allows us to show this previously discrete variable as a continuous variable. The sound of an engine's RPM is something that many people naturally use as an indicator of the engine's health. Thus, it is a good candidate variable for monitoring using sonification. The goals of the RPM sonification would be an ambient sound that would alert the operator to low and high RPM events without becoming overly distracting.

2.2.4.1 Related Sonifications

A quick review of the literature showed no examples where RPM has been sonified. Some reasons for this may be because engine RPM already has a strong auditory component that many individuals recognize. However, in a UAV, where the operator is removed from the actual vehicle, an auditory representation of RPM would be necessary. There are similar examples of sonifications which have been used to convey aircraft information. One example is a sonification designed by Watson, Sanderson, and Anderson (2000) that described a complex sonification for aircraft landing. In this sonification used a mapping involving the 3-D location of the sound, order, pitch, timbre, and tempo. The 3-D location of the sound represented the direction of deviation from the approach path. Airspeed was mapped onto the tempo of the sonification. The throttle and the mode of flight were mapped onto the pitch and the timbre of the sonification. Finally, the different engines could be differentiated by the order of the sounds. This sonification is quite complex and makes use of multiple characteristics of the carrier signal. A sonification for engine RPM could be much simpler and due to simplicity it may be possible to also provide additional redundancy by using multiple characteristics to represent the same changes.

2.2.4.2 Potential Mappings for RPM

The following are a few proposed methods for mapping engine RPM onto auditory characteristics. These auditory characteristics can be applied to a repeating auditory carrier signal. The ranges for these mappings will need to be further explored once the ranges for engine RPM are known, but these mappings should provide some ideas about how we can represent the data as an auditory signal. A final sonification combining all of these mappings may be the best method for creating such a sonification.

2.2.4.2.1 Pitch Mapping of RPM

The first method for mapping RPM data to a sound is to have RPM mapped onto pitch. This would be a simple mapping, with high pitch representing high engine RPM and low pitch representing low engine RPM. While pitch may not be the most influential auditory component for conveying auditory urgency (Hellier & Edworthy, 1999), it is a highly recognizable auditory characteristic that should be easily interpreted by most operators.

2.2.4.2.2 Tempo Mapping of RPM

Another possible method for mapping RPM data to sound is to change the tempo as the RPM changes. This is intuitive because higher RPM normally correlates with faster tempos of sounds coming from the engine. Similarly, low RPM would map intuitively onto a slow tempo. Speed is a very influential parameter for auditory urgency (Hellier & Edworthy, 1999), thus high engine RPM sounds will probably be perceived as highly urgent. Low engine RPM on the other hand may not be given the same advantages in urgency, as low engine RPM essentially generates "less noise." This could be counter-intuitive as a low engine RPM situation may be as, or more, critical than a high engine RPM situation. However, the mapping is ecologically valid as in an actual turboprop driven aircraft (such as the Heron), lower engine RPM would result in a lower tempo of the propellers. In the case of trained pilots, this may be a condition they are sensitive to and low tempos may retain a sense of urgency.

2.2.4.2.3 Timbre Mapping of RPM

Another way of showing high and low engine RPM is by alerting the operator to when the engine RPM deviates from the norm. This can be represented through the use of the sonification of timbre. At high and low engine RPM, engines tend to start producing sounds that are not heard during normal operation. This can be represented in the sonification by changing the quality of the sound. During normal RPM values, the sound of the sonification can be "noisier" or "messier." Hopefully, this will lead to a sound that is less intrusive and one that sounds similar to a UAV engine's normal operating sound. As engine RPM deviates from the norm or average RPM, the sound can become crisper and clearer. This may cause the sound to become more noticeable to the operator.

2.2.4.2.4 Combined Mappings

The various mappings could be combined so that RPM was mapped to pitch, tempo, and potentially timbre. The additional redundancy provided by the combined mapping may increase the salience of the display. With the mappings combined, the sonification would be as follows:

Normal RPM: noisy, mid pitch, mid tempo

High RPM: clear, high pitch, high tempo

Low RPM: clear, low pitch, low tempo.

2.2.4.2.5   Attentional and Urgency Mapping for Engine RPM

Another important concept to consider when designing the auditory sonification is the urgency mapping that would best support the monitoring task. Different auditory characteristics lead to different subjective perceptions of urgency (Hellier & Edworthy, 1999). This is a concept that can be used to create alarms of different priorities or to indicate situations that require more immediate responses in an intuitive manner (Arrabito et al, 2004). A similar concept which is applied more directly to sonifications is the idea of attentional mapping (Sanderson et al., 2000). Attentional mapping is an extension to Ecological Interface Design, where explicit mappings for where attention should be directed during different system states is designed. The goal is to create shifts of attention from peripheral to focal awareness when a signal moves from a normal state to an abnormal state. For monitoring engine RPM there are two abnormal states and one normal state. Both low and high RPM indicate a problem has occurred, with low RPM being more urgent than high RPM. Normal engine RPM, on the other hand, should provide the user with ambient feedback without being salient.

Attentional and urgency mapping can differ from the simple coding for engine RPM into variables such as pitch, tempo, and timbre. For example, it is simple and intuitive to map the speed to the engine to pitch, however, high pitch is perceived as more urgent than low pitch (Hellier & Edworthy, 1999). Thus, even though low pitch can be easily interpreted as representing low engine RPM, the urgency mapping would be inappropriate. Ideally, the engine RPM sonification would be composed of two components: the information content (the engine RPM) and how critical the information is (the urgency). To achieve this we propose a simple saliency mapping that uses both tempo and pitch. Pitch would still be used to indicate the information content of the sonification (i.e., the engine RPM with low pitch representing low engine RPM and high pitch representing high engine RPM) and with tempo representing the saliency mapping component (with low tempo representing normal situations and high tempo representing high urgency situations). To create the correct attentional mapping, it would be important to have a very low saliency tempo used for normal engine RPM which would increase gradually as the engine RPM either rose or fell. It would still be important to ensure that the tempo mapping for low engine RPM would increase at a faster rate than the tempo mapping for high engine RPM to retain the greater urgency that low engine RPM represents. Further experimentation to understand these mappings would still be required.

The proposed attentional and urgency mappings are as follows:

Normal RPM: mid pitch, slow tempo

High RPM: high pitch, high tempo

Low RPM: low pitch, highest tempo

2.3   Conclusion

In this chapter we examined the current literature on auditory and tactile design in UAV simulation environments and provided descriptions of a number of different auditory and tactile designs which can be used to increase operator awareness during UAV autoland scenarios. One of the lessons learned from the process of generating the auditory and tactile designs was that the design space for this problem is very large. There are a number of different variables that can be important to the monitoring of an automated UAV. The variables explored in this chapter include attitude upsets, system alerts and warnings, and engine RPM. While any of these variables may increase operator awareness, the task of finding which variables are most efficient at conveying information on the UAV's ability to land was beyond the scope of this current project. Even for the few variables discussed in this chapter, there are numerous methods for coding variables into the auditory and tactile display spaces. Where possible, we drew from previous literature to support our designs.

One issue that was especially difficult to judge in our designs was how much information is required to provide additional operator awareness. For example, individual roll, pitch, and yaw displays would provide the operator with a better overall understanding of the UAV's current situation. However, the additional information provided over an aggregate display may not be required for an operator whose sole decision is whether to abort or follow through with the UAV recovery. Due to the limited options available to the operator, a simpler display may actually prove more useful. Through discussions with the scientific authority, two displays were chosen for further development. The aggregate attitude tactile vest display and the engine RPM sonification were refined and implemented in simple prototypes for testing. The following chapter describes the process of implementation and the simple experiment designed to test the capabilities of these auditory and tactile displays.

3 Auditory and Tactile Display Prototyping and Testing

In this chapter we focus on the development and prototyping of a tactile and auditory display first proposed in Sections 2.2.2 and 2.2.4. An aggregate attitude upset tactile display and an engine RPM sonification were chosen for further refinement and development. Our goal was to explore how to implement these displays using the hardware provided and to develop a simple testing methodology for evaluating how participants would respond to the different interface ideas.

3.1 Auditory Stimuli Generation

In this section of the report, the generation and coding of the auditory stimuli are discussed. In particular, we developed three different kinds of sounds. The first was based on a real aircraft propeller engine. The second was generated using the same aircraft sound but with changes in the tempo of the sound. Finally, we created a sonification using pure tones. A sonification is used to present a data variable through a continuous auditory signal, in this case the auditory signals used were a propeller sound signal and a pure tone signal. The propeller sound is more realistic, but more complex to generate. The propeller sound with tempo is even more complex, but allows us to increase the amount of information conveyed. The pure tone based sound is less realistic but much simpler to generate. The following sections explain the steps that occurred to generate the auditory stimuli.

3.1.1 Generating Signals

A Tucker Davis RP2.1 Real-Time audio processor (Tucker Davis Technologies, 2011; shown in Figure 3.1) was the audio signal generator and acquisition hardware used for generating the signals for each of our auditory displays.

Figure 3.1: Tucker Davis RP2.1 Real-Time audio processor. (Image taken from Tucker Davis Technologies, 2011).

The RP2.1 audio processor can be controlled through software provided by Tucker Davis Real-Time Processor Visual Design Studio (RPvdsEX; Tucker Davis Technologies, 2011). This software has a visual design environment that is flexible, easy to use, and allows users to create custom signal processing programs without writing complex code. The programming environment provides different signal processing components in the form of blocks which can be selected and placed simply to create custom audio processing circuits. Audio circuits can then be

programmed into the RP2.1 audio processor. In the following sections we will describe the auditory circuits used to generate the different auditory displays.

3.1.2 Generating Propeller Engine Sounds

For generating a complex signal like a propeller engine sound, we need to know the constituent frequencies of that signal. We also need to know the amplitudes of the individual notes involved in the complex signal. A Fourier transform is a mathematical operation that can identify the constituent frequencies and their amplitudes. Essentially, a Fourier transform decomposes a complex signal into simpler oscillatory signals.

The sound of a real propeller engine, working at normal RPM, was recorded in the form of a WAV file. This file was provided by Defence Research and Development Canada (DRDC) Ottawa. Fourier transform operations were performed by inserting the WAV file into a computer program designed to execute the desired Fourier transforms. This program was written using the MATLAB programming language.
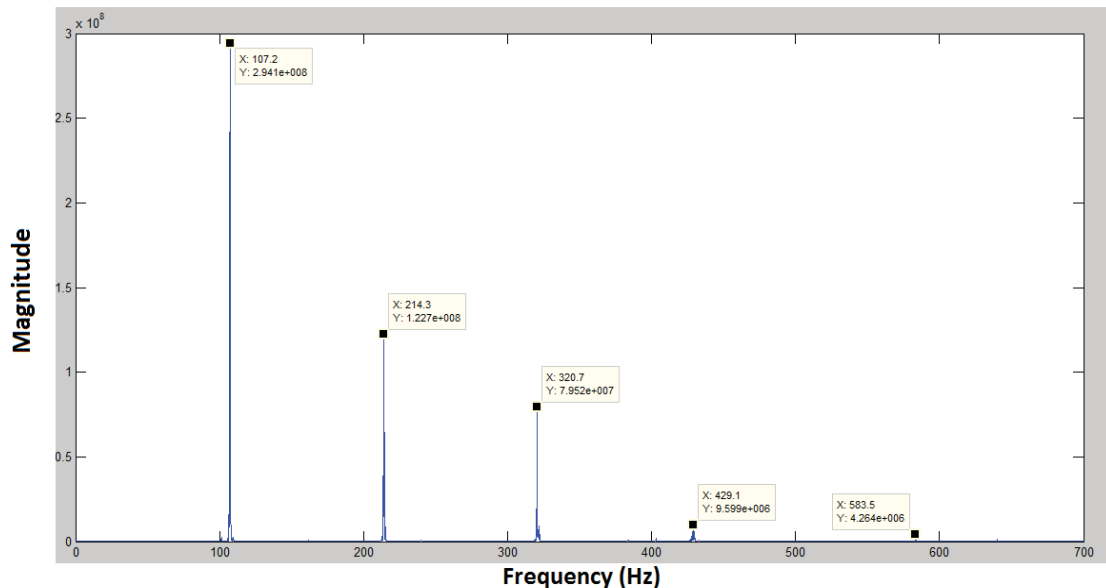

Figure 3.2: Results of the Fourier transform of the propeller engine sound.

According to the Fourier transform results which are depicted in Figure 3.2, the propeller engine sound is a signal which can be structured by summing up a series of sine wave signals at 107.2, 214.3, 320.7, 429.1, and 583.5 Hz with the magnitudes of 2.94, 1.22, 0.79, 0.09, and 0.04 respectively. The fundamental frequency is 107.2Hz and the other frequencies are approximately the multiples of the fundamental frequency. It should be noted that there is no dimension for the magnitude of the constituent signals. The vertical axis of the Fourier transform results represent the ratio of magnitudes of the constituent signals in regards to each other. The design objective was to create a sound with a similar frequency profile to this sound.

Figure 3.3 illustrates the audio circuit that we designed to generate the propeller engine sound. As can be seen in Figure 3.3, the circuit is comprised of 8 blocks. In the following sections, the blocks are described in more detail.
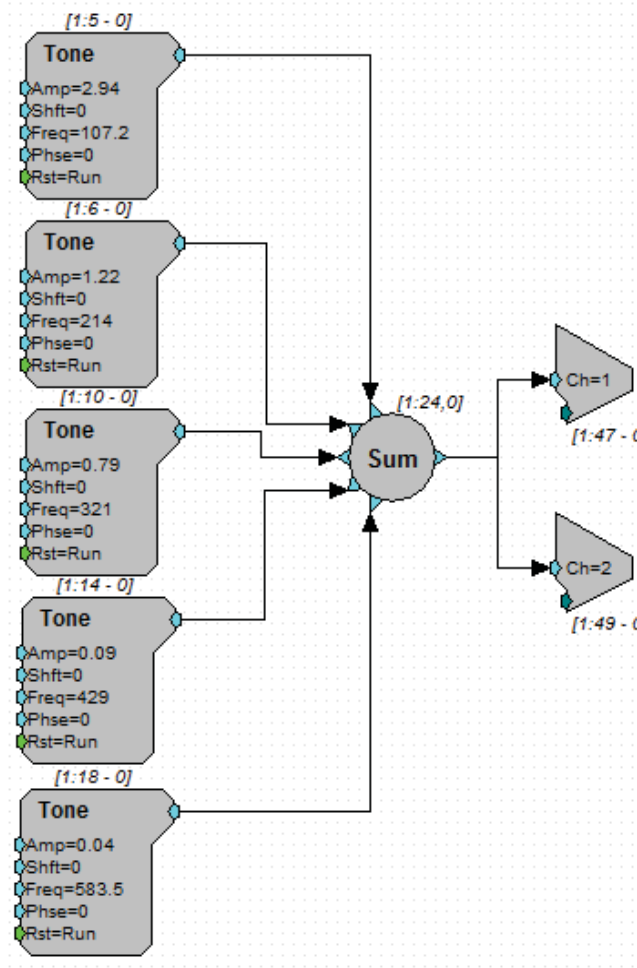
Figure 3.3: Screen shot of the RPvdxEX software. The audio circuit for generating the propeller engine sound.

3.1.2.1　Tone

Tone is a circuit component which generates a sinusoid waveform with a specific frequency and amplitude (Tucker Davis Technologies, 2011). As mentioned previously, a propeller engine sound can be generated by adding a series of sinusoid signals at specific frequency and amplitude levels. We used 5 blocks of *Tone* in our design in order to provide the sine waves required to produce the propeller engine sound. Each tone block provides one of the fundamental frequencies that were identified in the Fourier transform of the original signal. As well, the amplitude of each frequency component has been reconstructed in each *Tone* block.

3.1.2.2　Sum

Sum is a multi-input component that performs basic summation. It adds all of the input signals and provides the result at the time of output (Tucker Davis Technologies, 2011). As can be seen in Figure 3.3, all of the propeller engine constituent signals are given to the Sum as inputs. The resulting output is the desired engine sound.

3.1.2.3   DacOut (CH=1, CH=2)

A *DacOut* function block can be summarized as digital to analog conversion and provides a signal at the designated output channel (Tucker Davis Technologies, 2011). Sending a signal to a *DacOut* block allows users to listen to the generated signals using the proper headphones or speakers. The RP2.1 processor has 2 possible output channels (Two possible output channels allow for different signals to different ears or to different output devices). In this case, the propeller signal is being output on both audio outputs.

3.1.3   Propeller Engine Sound with Increasing/Decreasing RPM

The propeller engine sound discussed in Section 3.1.2 provides an auditory signal which presents the sound of a propeller engine under normal working conditions and at a normal RPM level. However, the proposed auditory display requires a design where sound varies at different RPM levels. Therefore, we decided to increase or decrease the constituent frequencies in a linear manner to map different RPM levels. Figure 3.4 illustrates an auditory circuit which was designed in the RPvdsEX software in order to generate a propeller engine sound with increasing RPM.

Considering Figure 3.4, A LinRamp is one of the auditory circuit components in RPvdsEX software which generates a linear ramp that begins at the min value and goes to the max value over a specified time (Tucker Davis Technologies, 2011). As we mentioned previously, the fundamental frequency of the propeller engine sound is 107.2Hz and the other constituent frequencies are approximately the multiples of the fundamental frequency. In order to simplify the design, we decided to feed the frequency of the *Tone* blocks from a single *LinRamp* source. In this case the *LinRamp* constantly sets the frequency of the *Tone* blocks over the time.

As can be seen in Figure 3.4 the min value of the *LinRamp* is 107.2, which is equal to the fundamental frequency of the propeller engine sound. In order to construct other constituent frequencies we used *Divide* blocks at the output of the *LinRamp*. A *Divide* block divides the input by the denominator and passes the quotient to the output (Tucker Davis Technologies, 2011).

In the auditory circuit depicted in Figure 3.4 the ramp time is 8000ms. If the ramp time decreases, the increment rate of the LinRamp increases. This results in the generation of a propeller engine sound which increases in pitch over time, representing an increase in RPM over time.
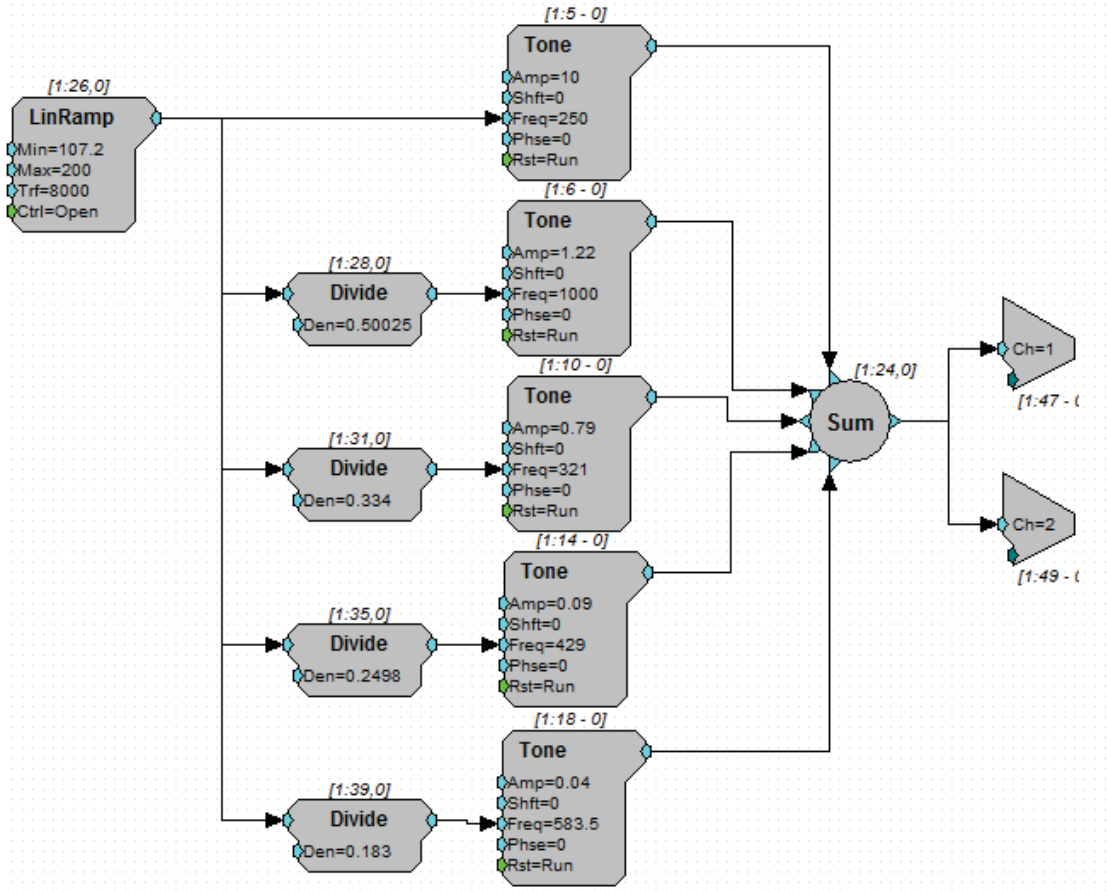
Figure 3.4: The audio circuit for generating the propeller engine sound with increasing RPM.

3.1.4 Adding Differing Tempo Rates to the Propeller Engine Sound as a Way of Displaying Different Levels of Urgency

As mentioned in the previous section, we can generate a propeller engine sound which varies RPM levels. In a real propeller engine, however, low and high RPM conditions are more critical than normal RPM conditions. In these cases we wanted to map urgency along with the propeller sound. In order to do this, we chose to control the tempo rate of the output signals, as a redundant factor, to show different levels of urgency (Edworthy et al., 1991). Controlling the tempo means activating and deactivating the output signals at different timing intervals. The timing of activation and deactivation needed to be a function of the changes in RPM levels.

As can be seen in Figure 3.5, the designed auditory circuit was comprised of two main parts. *Part I and Part II. Part I* is depicted with a red boundary and *Part II* is depicted with a blue boundary. In this auditory circuit the higher RPM urgency level is mapped onto faster tempo rates. The functionality of this circuit is such that the RPM level and the tempo rate of the generated sound starts at a constant level and remains steady for the first 10 seconds (Part I). After 10 seconds, the RPM and the tempo rates start to increase linearly for 20 seconds (Part II).
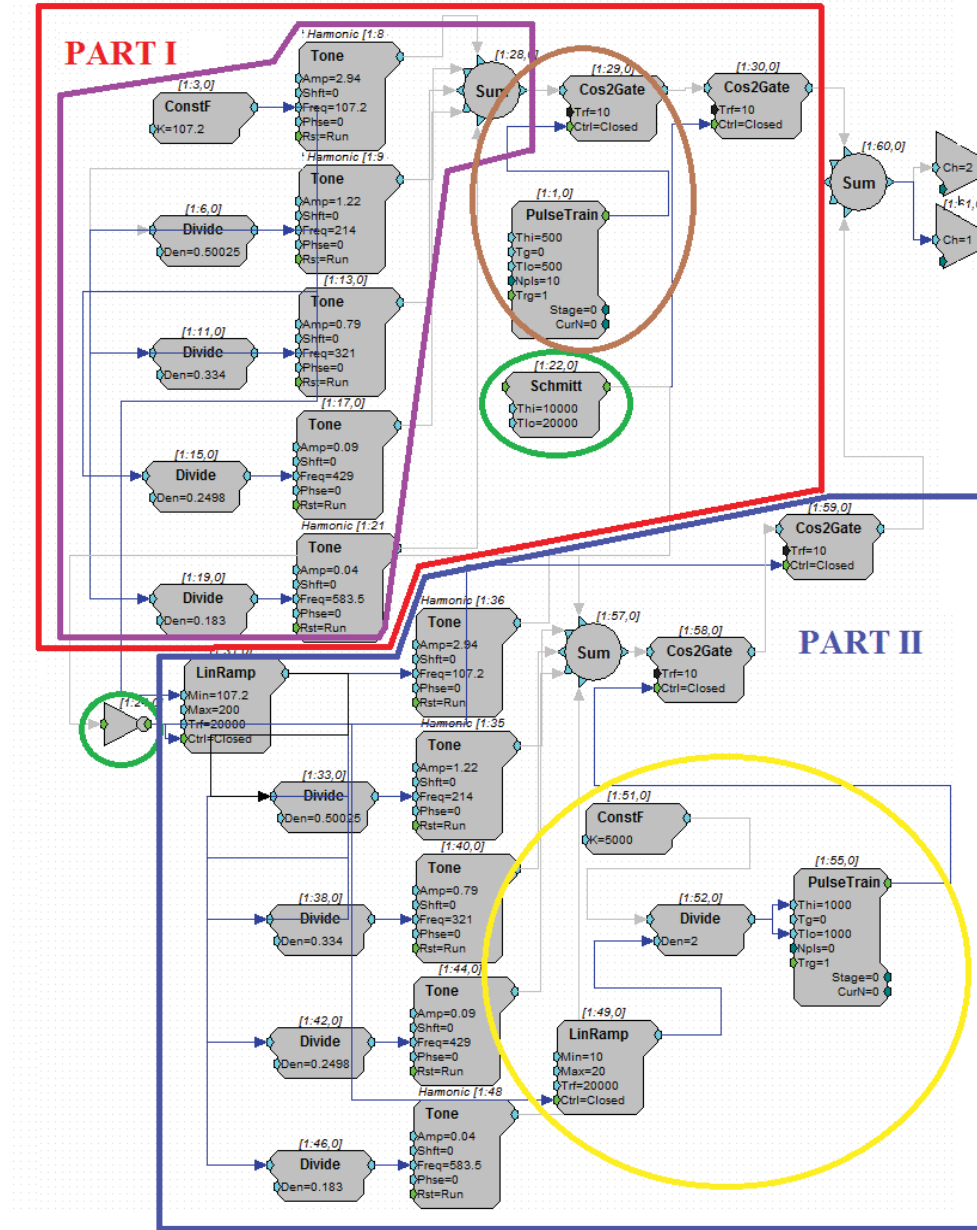
Figure 3.5: Adding different tempo rates to the propeller engine sound as a way of displaying different levels of urgency.

As can be seen in Figure 3.5, a combination of a *Schmitt* block and a *NOT gate* component (designated with the green circles) is included in the design of the proposed circuit, for switching purposes. A *Schmitt* block output goes to a high state for a set amount of time (determined by T_{hi}). At the end of the high time, the output goes to a low state for a set time (determined by T_{lo}). The combination of the *Schmitt* block and the *Not* gate here works like a digital switch. They stop *Part 1* of the circuit from transferring data to the output after 10 seconds and allow *Part II* of the circuit to transfer data to the output at the same time. We have provided detailed descriptions about each part in the following sub sections.

3.1.4.1   Part I

The major structure of the *Part I* circuit (depicted with a purple boundary in Figure 3.5) is very similar to the circuit which was illustrated in Figure 3.3. This part of the circuit generates a propeller engine sound which is working at a specific RPM level. The RPM level can be set by changing the fundamental frequency of the circuit through the *ConstF* block. In general a *ConstF* block provides a specific constant which can be inputted to any other block as an input.

This design gives us the capability to set the fundamental frequency more easily. For instance, if the desired starting fundamental frequency is 150Hz, we can change the value of the *ConstF* block to 150Hz. The other multiples of the fundamental frequencies will be generated automatically through the *Divide* blocks and will be inputted to the corresponding *Tone* blocks.

The resulting output of *Part I* of the circuit is a propeller engine sound which works at a specific RPM level (designated through the *ConstF* block value) with a tempo rate of 500ms *on* and 500ms *off*. The on/off action is carried out by modulating the output of circuit in the purple boundary through a subsequent modulating circuit (depicted in Figure 3.5 with a brown circle). The modulating circuit is comprised of a *PulseTrain* and a *Cos2Gate* block. A *PulseTrain* block generates logic pulse trains and turns the *Cos2Gate* block on and off at each 500ms time interval.

A *Cos2Gate* block functions as an enable line. The Cos2Gate will stay on and transfers data when its *CTRL* parameter value is *HI*. The rise time is the time it takes for the signal to reach 90% of the maximum value. The fall time is the time it takes the signal to reach 10% of the maximum value. The signal will start to decrease in frequency as soon as the *CTRL* value is low.

3.1.4.2   Part II

The resulting output of *Part II* of the circuit is a propeller engine sound with an increasing RPM level which causes the tempo of the generated signal to increase. As can be seen from Figure 3.5 the combination of *LinRamp*, *Divide*, *ConstF,* and *PulseTrain* blocks constructed the modulating circuit for this part (depicted with a yellow circle). The functionality of this part of the circuit is very similar to the modulating section of the *Part I* circuit. The difference here is that the on/off time linearly decreases over time.

3.1.5   Generating Pure Tone Sounds

The alternative to generating a realistic propeller sound was to generate a sonification built from pure tones.

Figure 3.6 illustrates an auditory circuit which generates a pure tone. As can be seen in

Figure 3.6, it is much easier to generate a sinusoid signal using the RP2.1 processor. It can be done by using only a *Tone* block and sending the output to a *DacOut*.
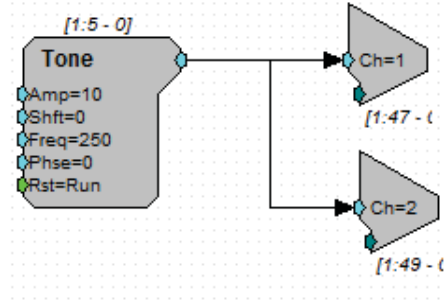
Figure 3.6: Generating a sine wave at 250Hz through RPvdsEX software.

It is possible to increase or decrease the frequency of a pure tone by adding additional blocks which will change the frequency that is inputted into the tone. Figure 3.7 illustrates an auditory circuit which generates a sine wave signal with decreasing frequency. The frequency of the generated signal starts at 250Hz and decreases to 0Hz over 10 seconds. Similarly, an increase in frequency can be achieved using a linear ramp that is inputted into the tone generator.
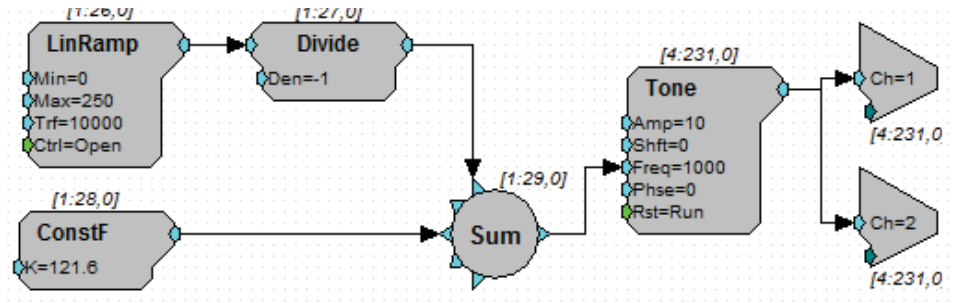

Figure 3.7: Generating a sine wave decreasing in frequency.

3.2 Attitude Upset Tactile Vest Implementation

In Section 2.2.2 we proposed some methods for displaying the attitude of an UAV using the vibrotactile vest. We suggest two main configurations. In the first configuration the C2 tactors formed a column of tactors and in the second configuration tactors were located in form of uni-centred circles.

Generally, as we move from distal regions (such as the hands) to proximal regions (such as the torso) of the body, the sensitivity to stimuli degrades. The law of mobility states that the skin's sensitivity to locating and discriminating touched locations improves as the mobility of parts of the body increases (Cholewiak, Brill, & Schwab, 2004; Van Erp, 2005b). Hence, displaying information through the uni-centred circle formation might be confusing for subjects. In addition, many of the more complex solutions discussed in Section 2 (such as the uni-centered circle formation, the yaw and pitch displays) require multiple tactors located on the front or back of a vest. The arrangement of some of these designs may not be possible given the recommended 3 cm tactor-to-tactor separation, and to maximize discriminability a simpler tactor layout would be required. After some discussions with DRDC and the research group, we concluded that using the *column of tactors* method would be a more effective solution for displaying information through the tactile vest. However, using one vertical column of tactors on the back or front side of the vest, aligned the observer's navel or spine, would be inefficient. The tactor vest does not have

good contact with the body surfaces in line with the spine or navel. Therefore, we decided to use a column of tactors to the left or right side of the spinal column in order to provide the necessary contact.

Decreasing the number of tactors can increase a participant's ability to discriminate between the different locations. As can be seen in Figure 3.8 some minor changes were made in the primary designs. We decided to reduce the number of tactors in a column from eight to four. This was done to ensure that each tactor would have sufficient spacing to increase detectability and discrimination. We also decided to position the tactors in the upper region of the back to ensure that the tactors on the vest would have contact with the skin. We found that even with a correctly fitted vest, tactors located in the lower region of the back would sometimes lose contact with the skin when the participant was seated. This may have been due to improper posture and slouching. We suggest that the tactors be placed at least 3 cm apart (edge-to-edge distance) as suggested by Van Erp (2005). The minimum separation of 3 cm was due to the spatial acuity of the torso, and tactors which are located closer than 3 cm apart may feel like they are originating from the same tactor. The entire four (or eight) tactor array will require 21 cm (9 cm for the inter-tactor spacing and 12 cm for the four tactors). From the NASA anthropometric data set, a 5th percentile 40 year old Japanese female has a waist-back measurement of 35.2 cm, so this display would take up roughly 60% of the participant's back. Similarly, the 95th percentile 40 year old American male has a waist-back measurement of 51 cm, which results in the display taking up just slightly over 40% of the participant's back. While we believe that these values are acceptable, future designs may require scaling of the inter-tactor distances to match variations in torso size, thus reducing the number of tactors used or the amount of space on the back used may need to be adjusted

It is also possible to reduce the inter-tactor spacing to 2cm, which is the lower bound of spatial acuity suggested by Van Erp (2005). However, this would only reduce the entire tactor configuration to 18 cm. This would still result in a display that would take up roughly 50% of the participant's back for a 5th percentile 40 year old Japanese female and roughly 35% of the participant's back for a 95th percentile 40 year old American male. Further investigation is needed to see if the loss in spatial acuity is outweighed by the benefits of having better skin contact due to the reduced size.
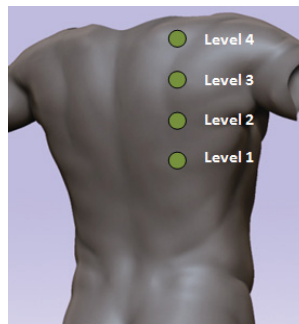

Figure 3.8: Reduced the number of tactors from eight to four and located them on the left or right side of the spinal column.

Based on the timing properties of the signals of the tactors, there are three main ways of attitude upset display using the column of tactors configuration. We have provided detailed descriptions about these methods in the following sections.

It should be noted that all of the described methods in this section can also be executed using two columns of tactors, one column on the left and one column on the right side of the spinal column. The purpose of using two columns of tactors would be to ensure that subjects receive the vibrations if a miss-contact happens in one of the columns. However the activation sequence would be identical for both columns.

3.2.1   Activation in Sequence

In this method of activation, the vertical distance of the activated tactor from the body's transverse plane presents the magnitude of the deviation. For example when the magnitude of the UAV's deviation changes from Level 1 to Level 2 (see Figure 3.8), the Level 1 tactor is deactivated and the Level 2 tactor is activated.

A C2 tactor's signal may vary in timing parameters. For example, it is possible to activate a tactor using signals which are different in terms of duty cycle or period. We have proposed some strategies for displaying information by using different duty cycles of the signals.

3.2.1.1   Activating all of the Tactors using Signals with a Same Duty Cycle

The signal is identical for the all four levels of tactors in this method. All of the tactors will be activated through a same signal at the time of activation. As can be seen in Figure 3.9, the period of the signal is 250ms and the duty cycle is 20%.
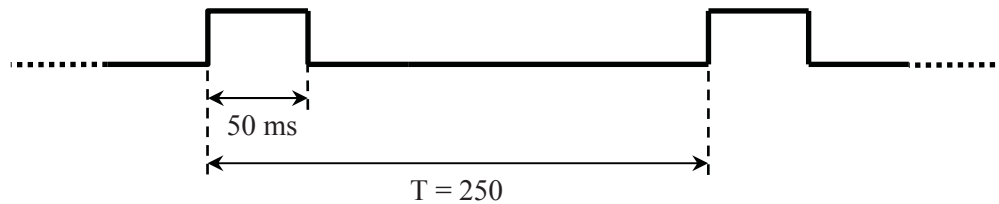

50 ms

T = 250

Figure 3.9: Signal with the period of 250 ms and the duty cycle of 20 %.

3.2.1.2   Activating the Tactors using Signals with Different Duty Cycles

In this method of activation, the signal for each level of tactors is different from the other levels (refer to Figure 3.10). The period of the signals are identical for all levels but the duty cycle increases as the level of the activated tactor increases. For example if the magnitude of the UAV's deviation is at the lowest level, the Level 1 tactor will be activated with a signal with a duty cycle at 20%. If the magnitude of the deviation increases, the Level 1 tactor is deactivated and the Level 2 tactor is activated by applying a signal with a duty cycle at 40%. In this method the duty cycle of the signal for the Level 3 and the Level 4 tactors are 60% and 80% respectively.
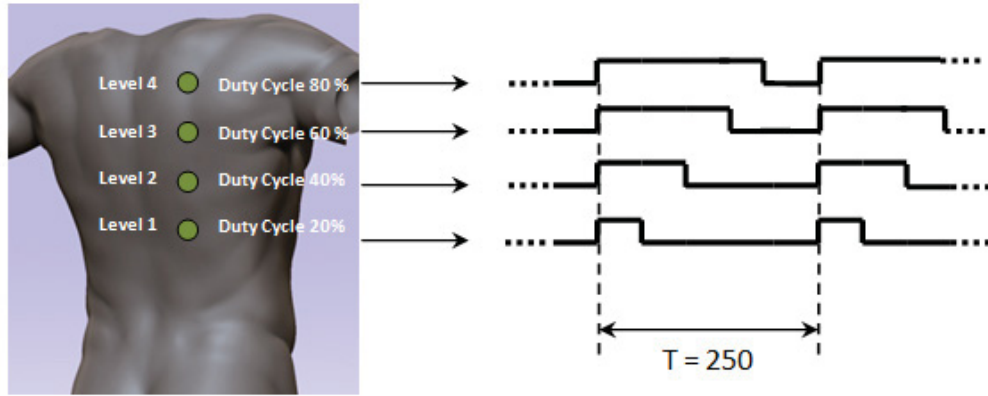
Figure 3.10: Activating the tactors using signals with different duty cycles.

3.2.2   Drawing Line of Tactors

Spatial-temporal patterns and perceptions of apparent movement can be generated by sequentially activating a series of vibrotactors placed on the skin (Cholewiak, & Collins, 2000). In this section we propose an activation method in which the magnitude of the UAV's deviations are presented in terms of linear patterns.

In this method the tactors are used to draw a line on the skin. The perceived length of the line presents the magnitude of the deviations. For example when the magnitude of the UAV's deviation is at Level 2, the Level 1 and Level 2 tactors will be sequentially activated. If the magnitude of the deviation increases, the Level 3 tactor will be added to the sequence. The activation timing is such that the *on-time* of the signals of the tactors located on two consecutive levels will have 20ms overlap. Figure 3.11 depicts the signals timings for the case in which all four tactors are being used to draw the tactile line.
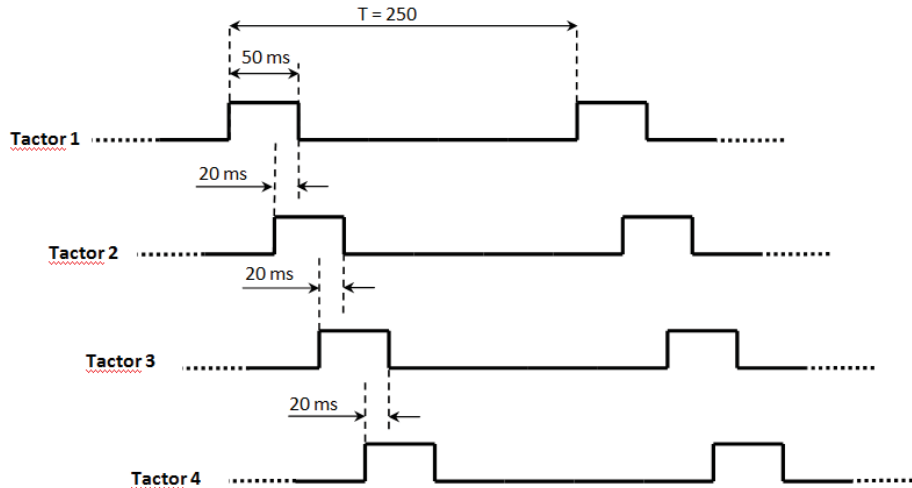

Figure 3.11: Sequentially activating tactors to generate a tactile line. The on-time of the signals of the tactors located on two consecutive levels has 20 ms overlap.

As can be seen from Figure 3.11, the signal is identical for all four levels of tactors in terms of period and duty cycle.

3.2.3   Equalizer Activation

As we mentioned previously, with this type of activation the number of activated tactors represents the magnitude of the deviation. In this mode, the tactor located on the lower level is not deactivated when the track deviation increases from one level to another.

3.2.3.1   Activating all of the Tactors using Signals with the Same Duty Cycle

Similar to in Section 1.1, the signal is identical for all four levels of tactors in this method. All of the tactors will be activated with the same signal at the time of activation. The period of the signal is 250ms and the duty cycle is 20%. The difference here is that when the attitude upset increases from one level to the next, all the tactors up to that level will stay activated.

3.2.3.2   Activating the Tactors using Signals with Different Duty Cycles

Similar to Section 3.2.1.2, in this method of activation the signal for each level of tactors is different from the other levels. The period of the signals are identical for all levels but the duty cycle increases as the level of the activated tactor increases. The duty cycle of the signal for Levels 1 through 4 are 20%, 40%, 60%, and 80% respectively. Again, in the equalizer activation mode, the tactor located on a lower level is not deactivated when the track deviation increases from one level to another.

3.3   Testing of Auditory and Tactile Designs

One of the goals of implementing the auditory and tactile designs first proposed in Section 2 was to subject the displays to short usability tests. As mentioned previously, the auditory and tactile design space is very large. Even with the initial design proposals, each design still had many possible design variations that required further testing. The usability test would be attempt to compare and contrast different variations of auditory and tactile displays and to examine how well they perform in terms of discriminability and urgency. It is important to note that these usability tests will help us gain an understanding about the different characteristics of our design, and the designs tested may not represent the final multimodal interfaces which will be used in the GCS. Instead, the results of these usability studies will be used to refine and augments the designs for the next phase of the GCS project.

3.3.1   Engine RPM Sonification

The auditory design chosen for further testing was the engine RPM sonification. The purpose of the sonification is to provide the GCS operator information about the UAV's current engine RPM value and to cue the operator to off-nominal situations when the engine RPM value is either too high or too low. The current baseline GCS interface makes use of visual warnings and a visual RPM value display to indicate whenever high or low engine RPM occurs. However, the visual warnings are discrete, and while they are highly salient when the operator is paying attention to the interface, and they do not provide the operator with any sort of situation awareness of a developing situation. The visual RPM value display does provide the operator with some awareness of the health of the situation, but this display is a small component of the display and operators may not be paying attention to the value.

In Section 3.1 we describe the implementation of three different types of displays based on the auditory characteristics of pitch, tempo, and timbre. In our first design we make use of a propeller engine like sound with the pitch of its fundamental frequency mapped onto the engine RPM. We used a mapping of higher pitch to represent higher engine RPM. In our second design, we used a complex propeller like sound which was augmented with a tempo mapping. As the engine RPM increases, so does the tempo of the sonification. The final design used a simple pure-tone which also mapped pitch to engine RPM. These three designs represent variations in terms of two factors: the base carrier signal (propeller like sound vs. pure tone) and whether tempo is used as an additional auditory characteristic (tempo change vs. no tempo change). These four designs represent some of the possible displays which we may test in our study. Further refinement is still required to narrow down the parameters and the displays which will be tested. In our usability test we will examine and compare these interfaces based on discriminability and urgency.

3.3.1.1   Discriminability of Auditory Sonifications

One question that is important to answer with regards to the sonifications is whether participants are able to easily discriminate between different levels of engine RPM on a perceptual level. The auditory designs will be tested using a "just noticeable difference paradigm". Up to 5 different levels will be pre-selected out of the range of the sonification display. During each trial, participants will experience one of the RPM levels as a stable auditory pattern for a short period of time, after which the sound or tactile pattern will either increase or decrease. Participants will be asked to indicate when they have noticed the pattern has changed by pressing a button and to indicate the direction of the change (increase or decrease). This will stop that trial. The pattern will be repeated at new level. All participants will experience repetitions of each trial for each design in a within subjects design. In half of the trials, the signal will increase and in 10 of the trials the signal will decrease. Increasing and decreasing of the signals will be randomized. Two times of onset of the change of the signal will occur, randomized so that the time of onset of the change of the signal cannot be anticipated a priori. The dependent variables will be response time, which is calculated from the start of the increase/decrease until the point where the participant responds, and the percentage of correct responses.

The main goal of the discriminability portion of the experiment is to examine differences between the two carrier signals (the propeller sound and the pure-tone). Since the signal will be continuous, we are interested in examining how the two different carrier signals would impact the participant's ability to detect changes. We are also interested in whether discriminability is affected by different starting pitches. If higher pitch signals produce sonifications that are easier to discriminate then we may shift up the range of frequencies used.

3.3.1.2   Urgency of Auditory Sonifications

During situations with high and low engine RPM, the operator is required to take action to ensure the safe recovery of the UAV. Thus, it is important that the sonification effectively alerts the operator to these situations. By encoding a sense of urgency into our sonifications, we can intuitively convey this type of information. Assessing the perceived urgency of the auditory displays will help us evaluate if this is being accomplished with our proposed designs.

To test the perceived urgency of the sonifications, participants will be presented with 5 different engine RPM levels repeated a number of times at each level and will be asked to provide a rating of urgency Each exposure will be quite short, lasting only about 5 seconds. The rating will be

provided on an urgency mapping scale based on Edworthy's urgency mapping principle and described in Arrabito et al. (2004). This scale is a simple scale between 1 and 100. The order of presentation of the levels will be randomized. The dependent variable will be the rating of perceived urgency.

3.3.2   Attitude Upset Tactile Display

A similar experiment will also be conducted for the attitude upset tactile display. The goal of the experiment will be to determine the tactor layout and activation pattern that will provide the best discriminability performance and provide the highest degree of urgency when required. The design of the experiment has still not been finalized. One factor that makes the evaluation of discriminability and urgency different from the auditory sonification is the discreteness of the tactile display. Instead of presenting a continuous signal, the tactile display uses discrete tactors that are only able to show levels of attitude upset. This requires different methods for evaluation of discriminability performance and may also change how urgency is rated by participants.

3.3.3   Experimental Parameters

There are still a number of experimental parameters that must be defined during the pilot study for this experiment. The following tables list each of the parameters that must be set for the discriminability task and the urgency task.

Table 2: Experimental parameters to be determined.

Parameter	Purpose
Number of pre-set levels.	These levels act as starting points for the signal to either increase or decrease from. It is important to cover the entire range of the display because the mappings used may have different levels of discriminability or urgency at different levels. For example, it may be easier to detect changes at high pitch than at low pitch.
Stimulus Onset Asynchrony (SOA)	SOA refers to the amount of time before the stimuli changes. The SOA varies so that the participant does not anticipate when a change would occur. We suspect that two levels will be sufficient for this purpose.
Number of replications	The number of times a trial for each display type is repeated.
Displays tested.	The types of auditory and tactile displays tested will still need to be determined. We have 4 auditory and 6 tactile designs to choose from, but it will not be possible to test each one of the displays due to time constraints.

3.3.4   Summary of Multimodal Display Testing

In this report, a number of different multimodal displays were proposed to supplement the baseline GCS. These displays varied in their complexity, the methods of information presentation, as well as many other dimensions. However, the feasibility and usability of the displays must first be determined before they can be selected for use in the multimodal GCS. In this section, two methods for examining the suitability of the auditory and tactile displays proposed were described: discriminability and urgency. Using these two metrics, the proposed designs can be tested using smaller scale experiments before implementation into the multimodal GCS is required. This will also allow for testing of various parameters for each design. Once the auditory and tactile designs are finalized, they can be implemented into the multimodal GCS for the next stage of the project.

4   Conclusion

The work covered in this report is in support of the CF JUSTAS Project. The work was performed in preparation for a large scale study comparing the two GCS designs. One of the GCS designs will be a visual interface, called the "baseline condition". The other design will be a multimodal interface where tactile and auditory information will be added to the interface. The overall goal of the GCS study is to support the future acquisition of a MALE UAV, and understanding the human monitoring challenges of this type of UAV. Two major activities were accomplished and described: the design of auditory and tactile stimuli for the multimodal condition of the GCS study, and preparation and testing for the baseline condition of the GCS study.

A literature review was completed on relevant auditory and tactile displays in UAV simulation environments. This literature was used to generate a number of different design proposals for multimodal displays. Two of these displays, an engine RPM sonification and aggregate attitude upset tactile display were chosen for further development and testing. These two interfaces were implemented using the hardware provided by DRDC-Toronto. A proposal for testing the displays was provided as a starting point for further discussion.

In preparation for the baseline GCS pilot study, ethics documentation from both the DRDC-Toronto and University of Waterloo ethics boards is provided. In addition, documentation of extensive testing of the experimental apparatus was conducted which included: identifying and correcting issues with the eye-tracking setup, identifying bugs with the GCS simulation, and set-up and placement of all apparatus and stimuli. The development of a training video was also documented. Overall, these activities have allowed us to reach a state of readiness to move on to the next stage of the project.

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List of symbols/abbreviations/acronyms/initialisms

[Enter list here, if applicable. If not, delete the page.]

DND	Department of National Defence
DRDC	Defence Research & Development Canada
DRDKIM	Director Research and Development Knowledge and Information Management
R&D	Research & Development